Leaf Tissue Nutrient Sufficiency Ranges of Four *Heuchera* Cultivars by Chronological Age

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**Abstract.** Coral bells (*Heuchera* spp.) are popular herbaceous perennials grown for their colorful foliage and venation and their aesthetic appeal in mixed containers and landscapes. Commercial coral bell production requires greenhouse or nursery growers to optimize production inputs such as managing mineral nutrition, thereby maximizing plant growth potential and foliage color. The objective of this study was to determine the optimum fertilizer concentrations, identify leaf tissue nutrient sufficiency ranges by chronological age, and to expand leaf tissue nutrient standards of coral bells grown in soilless substrates during container production. Coral bells (*H. hybrida* ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’), varying in leaf color, were grown under one of six constant liquid fertilizer concentrations [50, 75, 100, 200, 300, or 400 mg L\(^{-1}\) nitrogen (N)] with a constant level of water-soluble micronutrient blend in a greenhouse. Fertilizer concentrations for optimal plant growth and development were determined by analyzing plant height, diameter, growth index, and total dry mass, and were found to be 50 to 75 mg L\(^{-1}\) N after a nine-week crop cycle. Recently mature leaf tissue samples were collected and analyzed for elemental content of 11 nutrients at 3, 6, and 9 weeks after transplant (WAT) from plants fertilized with 50 to 75 mg L\(^{-1}\) N. The black- (‘Black Beauty’) and red- (‘Cherry Cola’) colored-leaved cultivars contained higher total N, phosphorus (P), potassium (K), calcium (Ca), sulfur (S), zinc (Zn), and boron (B) than the orange- (‘Marmalade’) and green- (‘Peppermint Spice’) colored-leaved cultivars. For instance, in mature growth, total N concentration for ‘Black Beauty’ and ‘Cherry Cola’ ranged between 3.45 to 3.63% and 3.92% to 4.18% N, respectively, whereas for ‘Marmalade’ and ‘Peppermint Spice’, ranges were between 2.98% to 3.25% and 2.78% to 3.23% N, respectively. Optimal leaf tissue concentration sufficiency ranges determined in this scientifically based study were narrower and often times higher than previously reported survey values for coral bells.

In the United States, coral bell (*Heuchera hybrida* L.) production increased by 167% ($14.4 million USD) from 1997 to 2014 (USDA, 1998, 2015). The increasing consumer demand for this herbaceous perennial is because of their colorful foliage and venation; mounding growth habit; use in mixed combination containers or landscape plantings; use as pollinator plants and cut flowers; and their drought- and deer-resistance. To continue to meet the increasing consumer demand for coral bells, greenhouse and nursery growers must optimize production inputs (Owen, 2019), such as fertilization. Traditionally, commercial mineral nutrition recommendations for the genera *Heuchera* range from 50 to 250 mg L\(^{-1}\) nitrogen (N) on a continual basis (Biernbaum and Morrison, 2000; Pilon, 2006) or 150 to 200 mg L\(^{-1}\) N as needed (Nau, 2011; Pilon, 2006). These fertility recommendations vary greatly, but the goal of any fertilizer regimen for containerized ornamentals is to provide sufficient but not excessive levels of essential nutrients (Scoggins, 2005). The philosophy of this approach is to monitor the inputs to the crop; and as along as the substrate inputs are within the recommended range, e.g., substrate pH and electrical conductivity (EC), it is assumed the fertility requirements of the crop are being met (Krug et al., 2010). This is consistent with nutritional requirements and nutritional status of container-grown coral bells by chronological age or as plants developed.

For herbaceous perennials, leaf tissue nutrient sufficiency ranges by chronological age have only been reported for perennial hibiscus (*Hibiscus hybridus* L. ‘Mocha Moon’ and ‘Starry Starry Night’; Owen, 2019). For annual bedding plants, leaf tissue nutrient sufficiency ranges by chronological age have been reported for pot gerbera (*Gerbera jamesonii* Bolus ex Hook. f. ‘Festival Light Eye Yellow’; Jeong et al., 2009), osteospermum (*Osteospermum hybridus* L. ‘Lemon Symphony’, ‘Serenity Lavender Dark’, ‘Summertime Red Velvet’, and ‘Tradewinds Purple Bicolor’; Papineau and Krug, 2014), and zonal geranium (*Pelargonium x hortorum* L.H. Bailey ‘Tango Dark Red’ and ‘Rocky Mountain Dark Red’; Krug et al., 2010). Determining sufficiency ranges and leaf nutritional standards by chronological age for the genera *Heuchera* will establish nutrient recommendations that may aid in identifying nutritional deficiencies and/or toxicities (Owen, 2019) and further define fertilizer recommendations. Therefore, the objectives of this study were to determine the optimum fertilizer concentrations, identify leaf tissue nutrient sufficiency ranges by chronological age, and to expand leaf tissue nutrient standards of coral bells grown in soilless substrates during container production.

**Materials and Methods**  
Plant material and culture. On 27 Sept. 2017, 72-cell plug trays of coral bells (*Heuchera hybrida* L. ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’) were received from a commercial supplier (Ball Horticultural Co., West Chicago, IL). Young plants of each cultivar with similar heights,
stem caliper, and node numbers were selected and transplanted, one plant per 16.5-cm (1.9-L) diameter container (Landmark Plastic Corp., Akron, OH). Containers were filled with premoistened, commercial soilless peat-based substrate comprised of (by volume) 65% peat, 20% perlite, and 15% vermiculite, amended with dolomitic limestone, wetting agent, and a starter nutrient charge with gypsum (Fafard 2; SunGro Horticulture, Agawam, MA). Substrate physical properties were determined using three representative samples that were analyzed using the North Carolina State University Porometer Procedure (Fonteno et al., 1995). Physical properties of the substrate were (by volume) 8.3% ± 0.8% air space, 77.9% ± 0.8% total porosity, 69.5% ± 0.5% container capacity, and 0.10 g-cm⁻³ bulk density. Plants were irrigated to container capacity with water supplemented with 35% sulfuric acid (AutoCraft Battery Acid, Johnson Controls Battery Group, Milwaukee, WI) at 0.16 mg L⁻¹ to neutralize alkalinity from 4.0 to 1.6 meq L⁻¹ calcium carbonate (CaCO₃) and reduce pH from 7.3 to a range of 5.8 to 6.0.

Plant fertility. Thirty-six plants per cultivar were placed on one of four greenhouse benches. Each bench was equipped with three independently controlled benchtop 1.9-cm black irrigation lines fitted with twenty-four 12-cm diameter drip rings (Dramm USA, Manitowoc, WI) that were placed on top of the substrate of each container, corresponding to one of six fertilizer concentrations. Each of the six fertilizer concentrations was replicated twice, for a total of 12 irrigation lines. These lines were randomized in two blocks, each consisting of two benches. Irrigation lines were connected to sump-pumps (model 1A, Little Giant Pump Co., Oklahoma City, OK), with three fertilizer concentrations arranged in a split-plot, with 2 replications within each split-plot. Cultivars were randomized within each replication. There were 3 experimental units per cultivar, per fertilizer concentrations, per replication. Within each block, no significant differences occurred among replications per cultivar; therefore, data were pooled. Effects of fertilizer concentrations per cultivar were analyzed using the Statistical Analysis System (SAS; version 9.2; SAS Institute, Cary, NC) general linear model procedure (PROC GLM) for ANOVA. For each cultivar, regression analyses of plant height, diameter, GI, and TDM at 9 WAT were performed using SAS regression procedure (PROC REG). For all analyses, a P ≤ 0.05 was used to determine significant effects.

Results and Discussion

Sufficiency range. Plant growth was analyzed to determine lower and upper optimal nutritional limits. At 9 WAT, the height, diameter, GI, and TDM were statistically similar for most all Heuchera cultivars fertilized with 50 to 400 mg L⁻¹ N (Table 1; Figs. 1–4). However, increasing fertilizer concentrations significantly influenced the diameter and TDM of ‘Cherry Cola’ and the TDM of ‘Peppermint Spice’ plants. For instance, plant diameter and TDM of ‘Cherry Cola’ decreased by 30.8% (9.9 cm) and 46.9% (3 g), respectively, as fertilizer concentration increased from 50 to 400 mg L⁻¹ N. Because Heuchera growth was generally similar or larger at 50 mg L⁻¹ N than at 75 to 400 mg L⁻¹ N, thus 50 mg L⁻¹ N was determined as the lower nutritional limit. Except for ‘Peppermint Spice’, plant growth of all other Heuchera cultivars was statistically similar among ascending fertilizer concentration from 75 to 400 mg L⁻¹ N (Table 1). Total dry mass of ‘Peppermint Spice’ was smallest at 50 mg L⁻¹ N, but it increased by 63.6% (4.2 g) as fertilizer concentrations increased from 50 to 75 mg L⁻¹ N. Smaller dry mass is likely attributed to fewer (to no) inflorescences present on plants fertilized at 50 mg L⁻¹ N than at 75 to 400 mg L⁻¹ N. Though TDM was not significantly influenced by increasing fertilizer concentrations for most all Heuchera cultivars, plants did, however, exhibit lower leaf necrosis at concentrations between 100 mg L⁻¹ N (personal observation). Lower leaf necrosis and smaller TDM for ‘Peppermint Spice’ is most likely attributed to sensitivity of an elevated substrate EC (Scoggins, 2005). For instance, average substrate EC extracted from all Heuchera cultivars grown at 100 to 400 mg L⁻¹ N were 2.98 to 4.22 mS cm⁻¹, respectively. They were 189% to 309% (1.95 to 3.19 mS cm⁻¹) and 135% to...
Table 1. Average plant height, diameter, growth indices (GI), and total plant dry mass (TDM) for coral bells (*Heuchera hybrida* L.) with black- (*Black Beauty*), red- (*Cherry Cola*), orange- (*Marmalade*), and green-colored leaves (*Peppermint Spice*). Plants were grown under one of six constant liquid fertilizer concentrations [50, 75, 100, 200, 300, or 400 mg L\(^{-1}\) nitrogen (N)], based on balanced ratios of N–phosphorous (P)–potassium (K) supplied by 15N–1.7P–12.5K containing 1.9% ammoniacal-N and 13.1% nitrate-N with a constant level of water-soluble micronutrient blend in a greenhouse. Plants (n = 6) were harvested at 9 weeks after transplant (WAT).

| Cultivar and nitrogen (N) concn (mg L\(^{-1}\) N) | Ht (cm) | Diam (cm) | GI (cm) | TDM (g) |
|-----------------------------------------------|--------|-----------|---------|---------|
| **Black Beauty**                              |        |           |         |         |
| 50                                           | 3.33   | 58.7      | 37.0    | 6.5     |
| 75                                           | 3.40   | 57.4      | 36.8    | 5.5     |
| 100                                          | 3.03   | 54.1      | 34.0    | 5.2     |
| 200                                          | 3.00   | 56.9      | 35.5    | 5.3     |
| 300                                          | 2.67   | 48.4      | 30.2    | 4.0     |
| 400                                          | 3.03   | 48.9      | 29.5    | 3.5     |
| **Significance**                              | NS     | L*        | L**     | L**     |
| **Cherry Cola**                               |        |           |         |         |
| 50                                           | 3.27   | 32.1      | 32.3    | 6.4     |
| 75                                           | 3.50   | 28.3      | 30.5    | 5.4     |
| 100                                          | 3.57   | 27.9      | 30.5    | 4.2     |
| 200                                          | 3.50   | 25.7      | 28.8    | 4.9     |
| 300                                          | 3.27   | 22.7      | 26.1    | 3.6     |
| 400                                          | 3.06   | 22.2      | 25.0    | 3.4     |
| **Significance**                              | NS     | L***      | NS      | L**     |
| **Marmalade**                                |        |           |         |         |
| 50                                           | 2.73   | 32.8      | 30.9    | 7.3     |
| 75                                           | 3.77   | 34.8      | 35.7    | 7.6     |
| 100                                          | 3.20   | 34.2      | 33.5    | 7.9     |
| 200                                          | 2.80   | 32.9      | 31.3    | 7.2     |
| 300                                          | 3.17   | 32.1      | 31.9    | 6.1     |
| 400                                          | 3.43   | 33.2      | 33.6    | 6.0     |
| **Significance**                              | NS     | NS        | NS      | NS      |
| **Peppermint Spice**                         |        |           |         |         |
| 50                                           | 1.70   | 31.4      | 26.6    | 6.6     |
| 75                                           | 2.07   | 31.0      | 27.6    | 13.1    |
| 100                                          | 1.73   | 32.5      | 27.5    | 10.8    |
| 200                                          | 2.20   | 28.7      | 26.4    | 10.6    |
| 300                                          | 1.93   | 25.1      | 23.3    | 9.1     |
| 400                                          | 2.17   | 30.1      | 27.3    | 9.1     |
| **Significance**                              | NS     | NS        | NS      | L*      |

\(^{a}\)Plant height (ht) measured from the substrate surface to the apical meristem.

\(^{b}\)Plant diameter (diam) determined by measuring the widest dimension and the axis perpendicular to the widest dimension and averaged.

\(^{c}\)Growth index (GI) = (plant height + plant diameter) \(\div\) 2.

\(^{d}\)Total plant dry mass (TDM) = young plant dry mass (YDM) + plant dry mass (PDM).

\(^{*}\)Linear (L) response for nitrogen (N) concentration. *NS* *NS* *NS* NS. *Not significant or significant at P \(\leq\) 0.05, 0.01, or 0.001, respectively.

232% (1.71–2.95 mS cm\(^{-1}\)) higher than average substrate EC values determined for plants fertilized at 50–75 mg L\(^{-1}\) N, respectively. Additionally, average substrate pH decreased by 19% (1.1 pH units), from 5.8 to 4.7 pH units, as fertilizer concentration increased from 50 to 400 mg L\(^{-1}\) N, respectively. Therefore, based on these results and visual observations, it was concluded that plants fertilized with \(\geq\)100 mg L\(^{-1}\) N were entering a situation of luxury to detrimental nutrient consumption, and the additional fertilizer was not beneficial to plant quality (Jeong et al., 2009; Krug et al., 2010; Owen, 2019; Papineau and Krug, 2014). When plant growth and substrate pH and EC data are taken together, 75 mg L\(^{-1}\) N was determined to be the upper nutritional range limit, and plants fertilized with 100 to 400 mg L\(^{-1}\) N were excluded from further statistical analyses. Thus, the optimal sufficiency range for all four *Heuchera* cultivars in this study was 50 to 75 mg L\(^{-1}\) N. Sufficiency ranges for all four *Heuchera* cultivars were used to determine recommend leaf tissue concentrations of eleven elements by chronological age. Similar to Owen (2019), lower and upper limits of recommended leaf tissue concentration ranges were defined by analyzing data for each *Heuchera* cultivar grown at 50 to 75 mg L\(^{-1}\) N over a 9-week crop cycle. Nutrient concentrations differed among cultivars with black- (*Black Beauty*), red- (*Cherry Cola*), orange- (*Marmalade*), and green-colored leaves (*Peppermint Spice*). No leaf tissue concentration limits have been published for *H. x sanguinea* Engelm., coral bell plants are reported by Bryson and Mills (2014)—but not *H. x micrantha* Douglas ex Lindl. ‘Palace Purple’ and nursery-grown (*H. sanguinea* Engelm.) coral bell plants are reported by Bryson and Mills (2014; Table 2). These tissue concentration ranges will be referred to as the genera *Heuchera*.

### Nitrogen

Total N [NO\(_3\)- N and NH\(_4\)- N] concentration of *Heuchera* cultivars in this study harvested at 3, 6, and 9 WAT (Table 3) resulted in higher and broader sufficiency ranges than those previously reported for *H. x micrantha* (1.46% to 1.77% N) and *H. sanguinea* (1.26% to 1.45% N; Bryson and Mills, 2014)—but not *H. x sanguinea* ‘Firefly’ (5.5% N; Biernbaum and Morrison, 2000; Table 2). At all stages of growth, total N concentration was higher in plants fertilized with 75 mg L\(^{-1}\) N than with 50 mg L\(^{-1}\) N. In young growth (3 WAT), total N concentration of ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and

![Fig. 1. Depiction of coral bells (*Heuchera hybrida* L. ‘Black Beauty’) fertilized with one of six constant liquid fertilizer concentrations [50, 75, 100, 200, 300, or 400 mg L\(^{-1}\) nitrogen (N)], based on balanced ratios of N–phosphorous (P)–potassium (K) supplied by 15N–1.7P–12.5K containing 1.9% ammoniacal-N and 13.1% nitrate-N with a constant level of water-soluble micronutrient blend at 3, 9, and 9 weeks after transplant (WAT).](image1)

![Fig. 2. Depiction of coral bells (*Heuchera hybrida* L. ‘Cherry Cola’) fertilized with one of six constant liquid fertilizer concentrations [50, 75, 100, 200, 300, or 400 mg L\(^{-1}\) nitrogen (N)], based on balanced ratios of N–phosphorous (P)–potassium (K) supplied by 15N–1.7P–12.5K containing 1.9% ammoniacal-N and 13.1% nitrate-N with a constant level of water-soluble micronutrient blend at 3, 6, and 9 weeks after transplant (WAT).](image2)

![Fig. 3. Depiction of coral bells (*Heuchera hybrida* L. ‘Marmalade’) fertilized with one of six constant liquid fertilizer concentrations [50, 75, 100, 200, 300, or 400 mg L\(^{-1}\) nitrogen (N)], based on balanced ratios of N–phosphorous (P)–potassium (K) supplied by 15N–1.7P–12.5K containing 1.9% ammoniacal-N and 13.1% nitrate-N with a constant level of water-soluble micronutrient blend at 3, 6, and 9 weeks after transplant (WAT).](image3)
‘Peppermint Spice’ ranged from 3.43% to 3.83%, 3.82% to 3.96%, 3.24% to 3.27%, and 2.87% to 3.15% N, respectively (Table 3). Increased total N concentration occurred at 6 WAT (active growth), but decreased onward as plants matured. Total N concentration of mature growth (9 WAT) ranged from 3.45% to 3.63%, 3.92% to 4.18%, 2.98% to 3.25%, and 2.78% to 3.23% N for ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’, respectively. These results are consistent with Krug et al. (2010), who reported decreasing N concentration of geranium cultivars fertilized with 100 to 300 mg L⁻¹ N at young to mature growth stages (2 to 12 WAT). Interestingly, in this study, phenotypes with black- (‘Black Beauty’) or red-colored leaves (‘Cherry Cola’) had generally higher leaf tissue N concentration than orange- (‘Marmalade’) or green-colored leaves (‘Peppermint Spice’). Similarly, in the Krug et al. (2010) study, N concentration of geranium ‘Tango Dark Red’, with dark-colored leaves, was higher (3.99% to 4.15% N) than the range reported for ‘Rocky Mountain Red’ (3.62% to 4.02% N), with light-colored leaves. However, no correlation between N concentration and leaf color were determined nor the focus of this study. Urban (1918) reports a correlation between beet (Beta vulgaris L.) leaf color and N concentration, the darker leaves containing the most N and the lighter the least. Furthermore, Judkins and Wander (1949) found a significant correlation between increasing N application rate, leaf tissue N content, and leaf color in apple (Malus sp. Mill. ‘Delicious’, ‘Cortland’, and ‘Stayman Wine-sap’), grape (Vitis sp. L. ‘Concord’ and ‘Delaware’), and peach (Prunus persica (L.) Batsch ‘Halehaven’. Based on the work of Urban (1918) and Judkins and Wander (1949), it is speculated that ‘Black Beauty’ and ‘Cherry Cola’ had higher leaf tissue N concentration than ‘Marmalade’ and ‘Peppermint Spice’, due to their darker-colored leaves.

**Phosphorus.** The recommended range for leaf tissue P concentration for the genera Heuchera is between 0.20% and 0.29% P (Bryson and Mills, 2014; Table 2). In the current study, P concentrations for all Heuchera cultivars were higher and broader than those previously published by Bryson and Mills (2014), with the exception of mature growth of ‘Peppermint Spice’. Phosphorus uptake is greater in younger plants and decreases with maturity (Bryson and Mills, 2014), and this trend was observed in the current study. In general, for all cultivars grown with 50 to 75 mg L⁻¹ N, leaf tissue P concentration increased by 6 WAT (active growth) and then decreased at maturity (9 WAT; Table 3). This trend is consistent with those of gerbera (Jeong et al., 2009) and geranium ‘Tango Dark Red’ (Krug et al., 2010). Jeong et al. (2009) report that the P concentration of gerbera increased by 5 WAT and decreased at 8 WAT (bloom). At maturity (9 WAT), P concentrations of ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’ were between 0.52% to 0.55%, 0.64% to 0.68%, 0.37% to 0.39%, and 0.22% to 0.30% P, respectively (Table 3). Furthermore, P concentrations were higher in ‘Black Beauty’ and ‘Cherry Cola’ than in ‘Marmalade’ and ‘Peppermint Spice’ at all stages of growth, while Krug et al. (2010) report higher P concentration only in young growth (2 WAT) of geranium ‘Tango Dark Red’ than ‘Rocky Mountain Dark Red’. The variation in P concentration among cultivars is likely attributed to genetics, because P uptake is genetically determined and differs between species and cultivars (Bryson and Mills, 2014).

**Potassium.** The recommended range for leaf tissue K concentration for the genera Heuchera is between 1.09% and 2.88% K (Bryson and Mills, 2014; Table 2). Young leaf tissue K concentrations for ‘Black Beauty’, ‘Marmalade’, and ‘Peppermint Spice’ were similar to those reported by Bryson and Mills (2014), while K concentration of ‘Cherry Cola’ were higher and broader. For instance, at 3 WAT, K concentrations of ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’ were between 2.40% to 2.68%, 2.80% to 3.29%, 1.92% to 2.27%, and 1.64% to 1.70% K, respectively (Table 3). As plants matured, K concentration increased by 6 WAT and decreased at 9 WAT (mature growth/bloom), which is similar to osteospermum (Papainue and Krug, 2014), gerbera (Jeong et al., 2009), and perennial hibiscus (Owen, 2019)—but not gerbera (Jeong et al., 2009) or osteospermum (Papainue and Krug, 2014). The increased Ca concentration at 6 WAT may be attributed to the increased amount of NO₃⁻ (13.1%) than NH₄⁺ (1.9%) N provided by the fertilizer, because NO₃⁻ usually increases Ca uptake (Bryson and Mills, 2014). The decrease in Ca concentration from 6 to 9 WAT (active to mature growth/bloom) may be attributed to the antagonism and competitive uptake of K or high relative humidity in the greenhouse, thus limiting Ca movement to meristematic tissues (Bryson and Mills, 2014; Owen, 2019); however, no K deficiency symptoms were observed. Furthermore, the average substrate pH of plants fertilized with 50 to 75 mg L⁻¹ N was 5.8, which is optimal for Ca availability and noted by Owen (2019) for Hibiscus production. The recommended range for leaf tissue Mg concentration for the genera Heuchera is between 0.20% and 0.45% Mg (Bryson and Mills, 2014; Table 2). The magnesium concentration range for all Heuchera cultivars in this study were narrower but within range previously reported by Bryson and Mills (2014; Table 3). Magnesium concentration in young leaf tissue of ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’ at 3 WAT ranged between 0.39% to 0.41%, 0.41% to 0.44%, 0.25% to 0.27%, and 0.27% to 0.30% Mg, respectively. In mature plants (9 WAT), Mg concentration ranged between 0.31% to 0.33%, 0.35% to 0.37%, 0.23% to 0.24%, and 0.29% to 0.33% Mg for ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’. Similarly, Krug et al. (2010) reported increased K concentration of geranium ‘Tango Dark Red’, the dark-colored leaf at maturity. The higher range limit for ‘Cherry Cola’ may indicate that plants fertilized with 75 mg L⁻¹ N were supplied with more K than needed for their metabolic requirements (luxury consumption), thus K recommendations may be lower than observed in the current study. However, no K toxicity symptoms were observed in ‘Cherry Cola’ (personal observation).

**Calcium.** The recommended range for leaf tissue Ca concentration for the genera Heuchera is between 1.26% and 2.23% Ca (Bryson and Mills, 2014; Table 2). The previously published Ca concentration range for Heuchera is higher than those observed for ‘Black Beauty’, ‘Marmalade’, and ‘Peppermint Spice’, but not ‘Cherry Cola’ (Table 3). Calcium concentrations in young growth (3 WAT) were between 1.01% to 1.10%, 1.14% to 1.34%, 0.70% to 0.72%, and 0.89% to 0.94% Ca for ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’, respectively (Table 3). While Ca concentration should increase as plants mature (Krug et al., 2010), leaf tissue Ca concentrations of ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’ at 9 WAT decreased and were between 0.88% to 0.95%, 1.36% to 1.66%, 0.73% to 0.77%, and 1.15% to 1.21% Ca, respectively. The observed trend of increased Ca by 6 WAT (active growth) and decrease at maturity and bloom (9 WAT) is consistent with zonal geranium ‘Rocky Mountain Dark Red’ (Krug et al., 2010) and perennial hibiscus (Owen, 2019)—but not gerbera (Jeong et al., 2009) or osteospermum (Papainue and Krug, 2014). The increased Ca concentration at 6 WAT may be attributed to the increased amount of NO₃⁻ (13.1%) than NH₄⁺ (1.9%) N provided by the fertilizer, because NO₃⁻ usually increases Ca uptake (Bryson and Mills, 2014). The decrease in Ca concentration from 6 to 9 WAT (active to mature growth/bloom) may be attributed to the antagonism and competitive uptake of K or high relative humidity in the greenhouse, thus limiting Ca movement to meristematic tissues (Bryson and Mills, 2014; Owen, 2019); however, no Ca deficiency symptoms were observed. Furthermore, the average substrate pH of plants fertilized with 50 to 75 mg L⁻¹ N was 5.8, which is optimal for Ca availability and noted by Owen (2019) for Hibiscus production.
Table 2. Recommended leaf tissue ranges for *Heuchera micrantha* ‘Palace Purple’ and *H. sanguinea* previously published by Bryson and Mills (2014) and values reported for *H. sanguinea* ‘Firefly’ by Biernbaum and Morrison (2000).

| Elemental nutrients | Unit of measure | Bryson and Mills (2014)* | Biernbaum and Morrison (2000)* |
|---------------------|----------------|--------------------------|-------------------------------|
| Macronutrients      |                | *Heuchera micrantha* ‘Palace Purple’ | *Heuchera sanguinea* |
| Total nitrogen      | %             | 1.46–1.77                | 1.26–1.45                     |
| Phosphorus          |               | 0.20–0.29                | 0.16–0.28                     |
| Potassium           |               | 1.49–2.88                | 1.09–1.28                     |
| Calcium             |               | 1.26–1.88                | 1.47–2.23                     |
| Magnesium           |               | 0.32–0.45                | 0.20–0.29                     |
| Sulfur              |               | 0.13–0.25                | 0.10–0.14                     |

| Micronutrients      | Unit of measure | Bryson and Mills (2014)* | Biernbaum and Morrison (2000)* |
|---------------------|----------------|--------------------------|-------------------------------|
| Iron                | mg·kg⁻¹         | 35–77                    | 30–53                         |
| Manganese           |                | 34–77                    | 13–26                         |
| Zinc                |                | 20–34                    | 15–32                         |
| Copper              |                | 3–12                     | 1–4                           |
| Boron               |                | 22–47                    | 21–39                         |
| Sodium              |                | —                        | 32                            |

| Micronutrients      | Unit of measure | Bryson and Mills (2014)* | Biernbaum and Morrison (2000)* |
|---------------------|----------------|--------------------------|-------------------------------|
| Sodium              |                | —                        | 258                           |

*aRecommended leaf tissue range for *Heuchera micrantha* ‘Palace Purple’ and *H. sanguinea* previously published by Bryson and Mills (2014).
*bLeaf tissue values reported for *Heuchera sanguinea* ‘Firefly’ previously published by Biernbaum and Morrison (2000).
*Tissue sample from botanical garden/arboretum plants.
*Tissue sampled from container production nursery and botanical garden/arboretum plants.
*No previously reported recommended leaf tissue range for the genera *Heuchera* by Bryson and Mills (2014).

Table 3. Sufficiency ranges of 11 essential elemental nutrients determined at 3 (young growth), 6 (active growth), and 9 (mature growth and/or bloom) weeks after transplant (WAT) for coral bells (*Heuchera hybridus L.*) with black- ('Black Beauty'), red- ('Cherry Cola'), orange- ('Marmalade'), and green-colored leaves ('Peppermint Spice') grown (n = 6) under 50–75 mg·L⁻¹ nitrogen (N), based on balanced ratios of N–phosphorus (P)–potassium (K) supplied by 15N–1.7P–12.5K containing 1.9% ammoniacal-N and 13.1% nitrate-N with a constant level of water-soluble micronutrient blend.

| Cultivar and weeks after transplant (WAT) | Elemental nutrient | Micronutrients | Micronutrients |
|------------------------------------------|-------------------|----------------|----------------|
|                              | Elemental nutrient | Total nitrogen | Phosphorus      | Potassium      | Calcium       | Magnesium     | Sulfur         | Iron           | Manganese      | Copper         | Boron         |
| Black Beauty 3                    | Total nitrogen    | 3.43–3.83       | 0.55–0.58      | 2.40–2.68      | 1.01–1.16     | 0.39–0.41     | 0.38–0.39     | 105.2–155.0    | 61.9–72.2      | 34.9–39.4      | 6.3–7.1       |
| Cherry Cola 6                     | Total nitrogen    | 3.79–4.00       | 0.72–0.75      | 3.00–3.06      | 1.07–1.16     | 0.37–0.40     | 0.40–0.45     | 128.5–189.6    | 57.2–67.5      | 54.6–56.1      | 7.1–7.2       |
| Marmalade 9                       | Total nitrogen    | 3.45–3.63       | 0.52–0.55      | 2.21–2.27      | 0.88–0.95     | 0.31–0.33     | 0.45–0.57     | 124.2–145.5    | 43.7–44.7      | 56.4–59.4      | 9.7–9.8       |
| Peppermint Spice 3                | Total nitrogen    | 3.24–3.27       | 0.47–0.50      | 1.92–2.27      | 0.70–0.72     | 0.25–0.27     | 0.45–0.52     | 137.5–154.2    | 62.6–73.5      | 41.3–46.2      | 30.8–33.6     |

of geranium ‘Tango Dark Red’ and osteospermum from 2 to 12 WAT. A lower Mg concentration at 3 WAT in comparison with Mg concentration at 5 mg·L⁻¹ may be attributed to the antagonistic effect of K from the fertilizer source, reduced residual effect of the dolomitic limestone used to adjust substrate pH, or a dilution effect of dry mass and a consistent volume of MgSO₄ applied (Owen, 2019). Though leaf tissue Mg concentrations were within the recommended range, symptoms of Mg deficiency such as interveinal chlorosis would be difficult to observed because of the color and venation pattern of *Heuchera* leaves.

Sulfur. The recommended range for leaf tissue S concentration for the genera *Heuchera* is between 0.10% and 0.25% S (Bryson and Mills, 2014; Table 2). Unlike previous reports by Krug et al. (2010) and Papineau and Krug (2014), S concentration for all *Heuchera* cultivars in this study was higher and narrower than those previously reported by Bryson and Mills (2014; Table 3). In young plants (3 WAT), S concentration ranged between 0.38% to 0.39%, 0.41% to 0.47%, 0.45% to 0.52%, and 0.39% to 0.41% S for ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’, respectively (Table 3). At plants matured (9 WAT), S concentration for ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’ ranged between 0.45% to 0.57%, 0.59% to 0.66%, 0.45% to 0.59%, and 0.36% to 0.48% S, respectively. At 9 WAT, the lower range limits for ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’ were 350%, 490%, 350%, and 260% higher, respectively, than ranges previously published by Bryson and Mills (2014). Upper range limits at 9 WAT for ‘Black Beauty’, ‘Cherry Cola’, ‘Marmalade’, and ‘Peppermint Spice’ were 128%, 164%, 136%, and 52% higher, respectively, than ranges previously published by Bryson and Mills (2014). Leaf tissue S concentration was generally lower for ‘Peppermint Spice’ than ‘Cherry Cola’, which may be attributed to a dilution effect of dry mass because TDM was 0.2 to 7.7 g greater for ‘Peppermint Spice’ than ‘Cherry Cola’ fertilized with 50 to 75 mg·L⁻¹—though S deficiency was not observed.

Iron. The recommended range for leaf Fe concentration for the genera *Heuchera* is between 30 and 75 mg·kg⁻¹ Fe (Bryson and Mills, 2014; Table 2). Iron concentrations were higher than those published by Bryson and Mills (2014) for ‘Black Beauty’, ‘Cherry Cola’, and ‘Marmalade’, but not ‘Peppermint Spice’. The observed higher range for ‘Black Beauty’, ‘Cherry Cola’, and ‘Marmalade’ may likely be attributed to high K, which increases the mobility and solubility of Fe in plants (Bryson and Mills, 2014) than Fe toxicity, which is associated with a substrate pH <5.4. In the current study, substrate pH ranged from 5.7 ± 0.1 to 5.8 ± 0.2 for plants fertilized with 50 to 75 mg·L⁻¹ N at 3 to 9 WAT, respectively; no Fe toxicity symptoms, such as
lower leaf bronzing or necrosis, were observed. In young plants (3 WAT), Fe concentration ranged between 105 to 155, 117 to 137, 138 to 154, and 50 to 58 mg kg\(^{-1}\) for 'Black Beauty', 'Cherry Cola', 'Marmalade', and 'Peppermint Spice', respectively (Table 3). Similar to studies of gerbera (Jeong et al., 2009), perennial hibiscus (Owen, 2019), and osteospermum (Papineau and Krug, 2014), Fe concentration increased slightly from 3 to 6 WAT, but decreased onward as plants matured. At maturity/bloom (9 WAT), leaf tissue Fe concentration for 'Black Beauty', 'Cherry Cola', 'Marmalade', and 'Peppermint Spice' ranged between 124 to 146, 107 to 112, 148 to 203, and 52 to 65 mg kg\(^{-1}\), respectively.

Manganese. The recommended range for Mn concentration for the genera *Heuchera* is between 13 and 77 mg kg\(^{-1}\) Mn (Bryson and Mills, 2014; Table 2). In the current study, Mn concentrations were within a narrower range than previously published by Bryson and Mills (2014). Mn concentrations for 'Black Beauty', 'Cherry Cola', 'Marmalade', and 'Peppermint Spice' grown with 50 mg L\(^{-1}\) N decreased by 29%, 13%, 29%, and 16% (18.2, 8.8, 18.3, and 8.7 mg kg\(^{-1}\) Mn) beginning at 3 to 9 WAT, respectively (Table 3). Although Mn concentrations were narrower than previously published ranges, visual Mn deficiency symptomology was not observed in any of the *Heuchera* cultivars trialed. A similar response occurred for the upper optimal Mn range. Leaf tissue Mn concentration of 'Black Beauty', 'Cherry Cola', 'Marmalade', and 'Peppermint Spice' grown with 75 mg L\(^{-1}\) N decreased by 38%, 7%, 37%, and 21% (27.5, 5, 27.5 and 13.9 mg kg\(^{-1}\) Mn) beginning at 3 to 9 WAT, respectively. This is consistent with trends reported for geranium 'Rocky Mountain Red' (Krug et al., 2010), gerbera (Jeong, et al., 2009), perennial hibiscus (Owen, 2019), and osteospermum cultivars (Papineau and Krug, 2014).

Zinc. The recommended range for Zn concentration for the genera *Heuchera* is between 15 and 34 mg kg\(^{-1}\) Zn (Bryson and Mills, 2014; Table 2). Zn tissue concentrations in the current study were higher at all stages of growth for all *Heuchera* cultivars than those previously published. Lower and upper limits increased over time, similar to studies of gerbera (Jeong et al., 2009), perennial hibiscus (Owen, 2019), and osteospermum (Papineau and Krug, 2014), lower and upper limits for all *Heuchera* cultivars increased over time. In young growth (3 WAT), B concentration for 'Black Beauty', 'Cherry Cola', 'Marmalade', and 'Peppermint Spice' ranged between 28.0 to 0.0, 28.5, 36.6 to 38.2, 30.8 to 33.6, and 30.3 to 30.6 mg kg\(^{-1}\) B, respectively (Table 3). For mature (9 WAT) 'Black Beauty', 'Cherry Cola', 'Marmalade', and 'Peppermint Spice' plants, leaf tissue B concentration increased to ranges between 41.3 to 46.2, 65.3 to 67.5, 37.8 to 37.9, and 31.6 to 36.4 mg kg\(^{-1}\) B, respectively (Table 3). Boron. The recommended range for B concentration for the genera *Heuchera* is between 21 and 47 mg kg\(^{-1}\) B (Bryson and Mills, 2014; Table 2). Boron tissue concentrations in this study provide a narrower range limit than values reported by Bryson and Mills (2014), except for 'Cherry Cola', which were higher as plants matured. Though B concentration at 3 to 9 WAT for 'Cherry Cola' increased from 36.6 to 38.2 mg L\(^{-1}\) B to 65.3 to 67.5 mg kg\(^{-1}\) B, respectively, Bryson and Mills (2014) indicated average B concentration in dry plant tissue can range from 20 to 100 mg kg\(^{-1}\) B. Therefore, B concentrations observed for 'Cherry Cola' are within the general range. Like studies of gerbera (Jeong et al., 2009) and osteospermum (Papineau and Krug, 2014), lower and upper limits for all *Heuchera* cultivars increased over time. In young growth (3 WAT), B concentration for 'Black Beauty', 'Cherry Cola', 'Marmalade', and 'Peppermint Spice' ranges were between 28.0 to 0.0, 28.5, 36.6 to 38.2, 30.8 to 33.6, and 30.3 to 30.6 mg kg\(^{-1}\) B, respectively (Table 3). For mature (9 WAT) 'Black Beauty', 'Cherry Cola', 'Marmalade', and 'Peppermint Spice' plants, leaf tissue B concentration increased to ranges between 41.3 to 46.2, 65.3 to 67.5, 37.8 to 37.9, and 31.6 to 36.4 mg kg\(^{-1}\) B, respectively (Table 3).

Conclusion

For the four *H. hybrida* cultivars studied, maximum growth occurred when an optimal fertility level of 50 to 75 mg L\(^{-1}\) N and a constant level of micronutrients were provided. Leaf tissue sufficient ranges for *H. hybrida* 'Black Beauty', 'Cherry Cola', 'Marmalade', and 'Peppermint Spice' by chronological age were determined and established ranges that differentiate between black-, red-, orange-, and green-colored-leaved cultivars. Leaf tissue concentration sufficient ranges determined in this study are generally narrower or higher than those reported by Bryson and Mills (2014), which is likely due to investigating one cultivar of each leaf color. Therefore, studies investigating multiple cultivars with similar leaf colors and venations and other fertilizer sources is warranted before these values are used for all coral bells. Continued research investigating other popular herbaceous perennial species grown in soilless substrates during container production over time is needed, to thereby establish nutrient sufficient ranges by chronological age.

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