Hibiscus Leaf Tissue Nutrient Sufficiency Ranges by Chronological Age

William Garrett Owen¹

Department of Horticulture, Michigan State University, 1066 Bogue Street, East Lansing, MI 48824; and Tollgate Farm and Education Center, Michigan State University Extension, 28115 Meadowbrook Road, Novi, MI 48377

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Abstract. Perennial hibiscus (*Hibiscus* sp.) are popular summer-flowering plants that are grown in greenhouses or nurseries, where growers must optimize production inputs such as fertility to maximize plant growth and produce high-quality flowering crops. 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 *Hibiscus hybrid* L. (hibiscus) grown in soilless substrates during container production. Two cultivars of hibiscus (*H. hybrid* L. ‘Mocha Moon’ and ‘Starry Starry Night’) 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. The fertilizer concentrations sufficient for optimal plant growth and development were determined by analyzing plant height, diameter, growth index (GI), primary shoot caliper (PSC), and total dry mass, and they were found to be 100–300 mg·L⁻¹ N after an 8-week crop cycle. Recently, mature leaf tissue samples were collected and analyzed for elemental content of 12 nutrients at 2, 4, 6, and 8 weeks after transplant (WAT) from plants fertilized with 100–300 mg·L⁻¹ N. An overall trend of increasing sufficient tissue concentration over time was observed for total N, phosphorus (P), calcium (Ca), sulfur (S), zinc (Zn), copper (Cu), and boron (B), whereas a decreasing trend was observed for potassium (K), iron (Fe), manganese (Mn), and aluminum (Al). For instance, at 2 WAT, total N ranged from 3.1% to 5.1% N and increased to a range of 4.2% to 4.7% N at 8 WAT. At 2 WAT, Fe and Mn ranged from 79.2 to 103.6 mg·L⁻¹ Fe and 66.3–82.8 mg·L⁻¹ Mn and decreased to ranges of 75.6–82.9 mg·L⁻¹ Fe and 18.1–99.7 mg·L⁻¹ Mn at 8 WAT, respectively. Optimal leaf tissue concentration sufficiency ranges determined in this scientifically-based study were narrower than previously reported survey values for the genera *Hibiscus*.

Over the past decade, the United States herbaceous perennial sector, including garden chrysanthemum (*Chrysanthemum ×morifolium* Ramat.) and hosta (*Hosta* Tratt. sp.) categories, increased by 43% from 2005 to 2015 (USDA, 2006, 2016). To meet this increasing consumer demand for herbaceous perennials, producers

must optimize production inputs, understand environmental and cultural requirements, and minimize waste, thereby, consistently producing high-quality flowering crops. However, much of the literature available to perennial growers were established from research that occurred in the late 1990s to early 2000s and included propagation (Enfield, 2002), cold hardiness and overwintering [acclimation, freezing, and deacclimation (Herrick and Perry, 1997; Kingsley-Richards and Perry, 2011; Perry, 2011)], and forcing [vernalization, photoperiod, and temperature (Heins et al., 2000)] studies. Since then, new and ongoing herbaceous perennial research has surfaced including, propagation (Owen, 2017) and plant growth control (Latimer, 2016) studies, respectively.

To date, optimum fertilization requirements (Owen et al., 2013; Scoggins, 2005) and nutritional leaf tissue sufficiency ranges and standards (Barnes, 2010; Biernbaum and Morrison, 2000; Bryson and Mills, 2014; Dole and Wilkins, 2005; Zheng and Clark, 2013) of some herbaceous perennials have been reported. The largest collection of nutritional leaf tissue standards was established by Bryson and Mills (2014), but only 69% of the herbaceous perennial genera reported had

tissue samples that represent container-grown plants in greenhouse or nursery production. These published leaf tissue nutritional standards established for container-grown herbaceous perennials represent survey measurements, which provide a wide variability of recommended nutrient levels. Although more than half of the herbaceous perennial leaf tissue nutritional standards represent plants grown in containers, other perennial genera tissue samples were collected from plants grown in mineral soils located in botanical gardens, arboretums, experimental plots, or were field-grown (Bryson and Mills, 2014). Therefore, these nutritional standards do not accurately represent the nutritional status nor sufficiency ranges of herbaceous perennials grown by commercial operations in soilless substrates.

Little attention has been given to identifying nutrient requirements and nutritional status of container-grown plants as related to plant age or stage of development (Tolman et al., 1990). For instance, Bryson and Mills (2014) reported an estimated age and where the leaf tissue was sampled by stating “mature leaves from new growth,” while Campbell (2000) only reported leaf tissue standards for poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch) at “all growth stages.” However, for economically significant agronomic crops, such as corn (*Zea mays* L.), leaf nutrient sufficiency ranges were documented at the seedling (<4 inches), early growth (>4 inches to tasseling), tasseling/bloom, and maturity developmental stages (Campbell, 2000). In 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 hybrida* L. ‘Lemon Symphony’, ‘Serenity Lavender Dark’, ‘Summertime Red Velvet’, and ‘Tradewinds Purple Bicolor’; Papineau and Krug, 2014), and zonal geranium (*Pelargonium ×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 herbaceous perennials will establish nutrient recommendations that may aid in identifying nutritional deficiencies, toxicities or both. In addition, reporting of such information will establish optimal fertilizer recommendations. This is significant for commercial production because perennial growers provide plants anywhere from 50 to 700 mg·L⁻¹ N (Pilon, 2006). Established fertilizer recommendations will enable the potential avoidance of excess fertilization, leaching, and runoff contamination from container-grown herbaceous perennials in greenhouses or nurseries.

Thus, there is a need to establish optimum fertilization concentrations and expand leaf tissue nutritional standards for successful herbaceous perennial production. There is little information available regarding optimum fertility requirements for container-grown herbaceous perennials. Established

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¹Corresponding author. E-mail: wgowen@msu.edu.

leaf tissue nutritional standards are limited to only 73 herbaceous perennial genera grown in containers (Bryson and Mills, 2014), and to date, herbaceous perennial leaf tissue nutritional sufficiency ranges by chronological age have not been reported. 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 *H. hybrid* L. (hibiscus) grown in soilless substrates during container production. Hibiscus served as a model crop because to date, no leaf tissue concentration limits are published for *H. hybrid*, but only survey measurements taken from greenhouse- and nursery-grown hibiscus species are reported by Bryson and Mills (2014).

Materials and Methods

Plant material and culture. On 8 Apr. 2017, rooted 72-cell plug trays (30.7-mL individual cell volume) of two cultivars of hibiscus (*H. hybrid* L. ‘Mocha Moon’ and ‘Starry Starry Night’) were received from a commercial supplier (Walters Gardens, Inc., Zeeland, MI). Young plants of each cultivar with similar heights, stem calipers, 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 (by volume) 65% peat, 20% perlite, and 15% vermiculite, amended with dolomitic limestone, wetting agent, and a starter nutrient charge with gypsum (Fafard 2; Sun Gro Horticulture, Agawam, MA). Plants were irrigated to container capacity with water supplemented with 35% sulfuric acid (Auto-Craft 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 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 24, 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 that 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) which delivered one of the six constant liquid fertilizer concentrations (50, 75, 100, 200, 300, or 400 mg·L⁻¹ N) based on balanced ratios of N–P–K supplied by 15N–1.7P–12.5K (GreenCare Bordine’s Special; Blackmore Co., Belleville, MI), containing 1.9% ammoniacal (NH₄⁺)-N and 13.1% nitrate (NO₃⁻)-N. The fertilizer concentrations were selected based on grower practice and to

determine minimum and maximum sufficiency ranges.

Regardless of fertilizer treatment, plants received a constant level of water-soluble micronutrient blend (GreenCare Bordine’s Special; Blackmore Co.) supplying (in mg·L⁻¹) 2.0 Fe, 0.5 Mn and Zn, 0.25 B and Cu, and 0.1 molybdenum. The water-soluble fertilizer and micronutrient blend were weighed and dissolved together in 100-L fertilizer barrels. Plants were irrigated as needed to the point of leaching and were never allowed to dry out. Each month, plants received a 150-mL drench containing 50 mg·L⁻¹ magnesium sulfate (MgSO₄·7H₂O). No solution was leached or drained from the containers after application.

Greenhouse environment. Plants were grown in a double polyethylene-covered greenhouse with roll up side curtains [MSU Tollgate Farm and Education Center, Novi, MI (lat. 42°N)], at 20 °C, under ambient daylight supplemented with a photosynthetic photo flux density (PPFD) of ≈35.6 μmol·m⁻²·s⁻¹, at plant height [as measured with a quantum sensor (LI-190SL; LI-COR Biosciences, Lincoln, NE)], delivered from 150 W high-pressure sodium (HPS) lamps (Sun System® HPS 150 Grow Light Fixture; Sunlight Supply, Inc., Vancouver, WA) from 0600 to 2200 HR (16-h photoperiod). On each bench, an enclosed thermocouple recorded air temperature every 30 s and averages were logged every 15 min by a data logger (WatchDog Model 2475 Plant Growth Station; Spectrum Technologies, Inc., Aurora, IL). Line quantum sensors (SQ-316-SS; Apogee Instruments, Inc., Logan, UT) mounted 60 cm above the benchtop measured PPFD every 30 s and the average of each sensor was logged every 15 min by a data logger (WatchDog 2800 Weather Station; Spectrum Technologies, Inc.). Average daily light integral, air temperature and relative humidity throughout the 8-week duration of the experiment were 12.3 ± 4.7 mol·m⁻²·d⁻¹, 22.7 ± 2.2 °C, and 64.8% ± 6.2%, respectively.

Growth and nutritional data and calculations. Data were collected on three randomly selected experimental units (individual plants) of each cultivar. Data were collected at 2, 4, 6, and 8 WAT. At each collection date, substrate solution was extracted 1 h after irrigation using the pour-through method (Wright, 1986) and analyzed for pH and electrical conductivity (EC) using a HI 9813-6 portable meter (Hanna Instruments, Woonsocket, RI). Plant height was determined by measuring from the substrate surface to the apical meristem. Plant diameter was determined by measuring the widest dimension and the axis perpendicular to the widest dimension and averaging. Growth index [GI = (plant height + plant diameter)/2] was calculated for each plant. The PSC was determined by measuring below the lowest axillary shoot with a digital caliper (digiMax; Wiha, Schönach, Germany).

At 2, 4, 6, and 8 WAT, the recently mature (youngest fully expanded) leaves were removed from the selected three experimental

units from each cultivar. Leaves were washed in a solution of 0.5 N hydrochloric acid for 1 min and rinsed in deionized water before being individually bagged, and was dried in an oven at 70 °C for 1 week. After 1 week, dried tissue was weighed to determine young leaf dry mass (YDM) and ground with a mortar and pestle to pass a ≤0.5-mm sieve, placed in 15-mL polypropylene conical centrifuge tubes (Falcon 17 × 120 mm; Corning, Corning, NY), and analyzed for nutrient concentrations by AgSource Laboratories (Lincoln, NE). Total N was processed by Kjeldahl digestion and determined by flow injection analysis. Extractable K was processed by 2% acetic acid digestion and determined by inductively coupled plasma mass spectrometry (ICP-MS). Total P and all other plant minerals (Ca, Mg, Fe, Mn, Zn, B, Cu, and Al) were processed by nitric acid/hydrogen peroxide digestion, and determined by ICP-MS.

The remaining plant tissues were destructively harvested by severing the stem at the substrate surface, individually bagging and drying in an oven at 70 °C. After 1 week, plant dry mass (PDM) was determined. Total plant dry mass [TDM; (TDM = YDM + PDM)] was calculated for each plant.

Experimental design and statistical analyses. The experiment was laid out in a randomized complete block design with two blocks and six fertilizer concentrations arranged in a split-plot with two replicates within each split-plot. Cultivars were randomized within each replicate. There were three experimental units per cultivar per fertilizer concentrations per replicate. Within each block, no significant differences occurred among replicates per cultivar; therefore, data were pooled. The effects of fertilizer concentrations per cultivar were analyzed using SAS (version 9.2; SAS Institute, Cary, NC) general linear model procedure (PROC GLM) for analysis of variance, and means were separated between fertilizer concentrations using Tukey’s honestly significant differences. For each cultivar, regression analyses of foliar nutrient concentrations within WAT with fertilizer concentration as the independent variable were performed using SAS regression procedure (PROC REG). Regression models, equations, and adjusted-R² are provided in Table 1. For all analyses, a *P* ≤ 0.05 was used to determine significant effects.

Results and Discussion

Sufficiency range. At 8 WAT, increasing fertilizer concentrations significantly influenced plant height, diameter, GI, PSC, and TDM of both *Hibiscus* cultivars (Table 2; Figs. 1 and 2). Plant growth was analyzed to determine lower and upper optimal nutritional limits. The *Hibiscus* plants fertilized with 50 and 75 mg·L⁻¹ N resulted in similar and significantly smaller plant height, diameter, GI, PSC, and TDM than those fertilized with 100–400 mg·L⁻¹ N. Therefore, 100 mg·L⁻¹ N was determined as the lower

nutritional limit, and the plants fertilized with 50 and 75 mg·L⁻¹ N were excluded from further statistical analyses.

Plant growth of both *Hibiscus* cultivars was statistically similar among ascending fertilizer concentration from 100 to 400 mg·L⁻¹ N (Table 2). However, TDM of ‘Mocha Moon’ and ‘Starry Starry Night’ at increasing fertilizer concentrations of 300–400 mg·L⁻¹ N decreased by 12.5% (4.6 g) and 11.8% (4.2 g), respectively. Smaller TDM is most likely attributed to sensitivity of an elevated substrate EC (Scoggins, 2005). For

instance, average substrate EC extracted from ‘Mocha Moon’ and ‘Starry Starry Night’ grown at 400 mg·L⁻¹ N were 4.22 and 4.50 mS·cm⁻¹, respectively, and they were 30% to 929% (0.97–3.81 mS·cm⁻¹) and 32% to 1084% (1.08–4.12 mS·cm⁻¹) higher than the average substrate EC values determined for plants fertilized at 50–300 mg·L⁻¹ N, respectively. Furthermore, drawing from experience of common grower practices, fertilizer costs, and possible environmental impacts of excessive fertilization, it was concluded that plants fertilized

with ≥300 mg·L⁻¹ N would be entering a situation of luxury nutrient consumption and the additional fertilizer was not beneficial to plant quality (Jeong et al., 2009; Krug et al., 2010; Papineau and Krug, 2014). When TDM and substrate EC data are taken together, 300 mg·L⁻¹ N was determined as the upper nutritional range limit, and plants fertilized with 400 mg·L⁻¹ N were excluded from further statistical analyses. Thus, the optimal sufficiency range for both *Hibiscus* cultivars in this study is 100–300 mg·L⁻¹ N.

Table 1. Regression models, equation, and adjusted-*R*² for sufficiency ranges of macronutrients [nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S)] and micronutrients [iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and aluminum (Al)] over an 8-week crop cycle in two hibiscus (*Hibiscus hybrid* L. ‘Mocha Moon’ and ‘Starry Starry Night’) cultivars grown at 100–300 mg·L⁻¹ N. Data were pooled over cultivars.

Elemental nutrients	Unit of measure	N concn (mg·L ⁻¹ N)	Figure	Model ^z	Equation ^y	Adjusted- <i>R</i> ²
Macronutrients						
Total N	%	100	3 A	Q**	$y = 0.8251 + 1.2213x - 0.0971x^2$	0.5447
		300		Q***	$y = 4.3654 + 0.4386x - 0.0489x^2$	0.5008
P		100	3 B	Q***	$y = 0.1891 - 0.2763x - 0.0241x^2$	0.6722
		300		Q***	$y = 0.1844 + 0.2148x - 0.0208x^2$	0.9842
K		100	3 C	Q***	$y = 2.4944 + 0.4467x - 0.0544x^2$	0.0577
		300		L***	$y = 4.6408 - 0.1730x$	0.6661
Ca		100	3 D	Q***	$y = 0.3975 + 0.7573x - 0.0738x^2$	0.9414
		300		Q**	$y = 0.9925 + 0.6698x - 0.0702x^2$	0.7254
Mg		100	3 E	Q***	$y = 0.4663 + 0.1389x - 0.0181x^2$	0.8457
		300		Q**	$y = 0.4938 + 0.1638x - 0.0197x^2$	0.7651
S		100	3 F	Q***	$y = 0.0050 - 0.2151x - 0.0209x^2$	0.9669
		300		Q***	$y = 0.1038 + 0.2180x - 0.0033x^2$	0.9774
Micronutrients						
Fe	mg·L ⁻¹	100	4 A	Q**	$y = 38.2796 + 22.9996x - 2.0971x^2$	0.2338
		300		Q**	$y = 54.0208 + 31.3700x - 3.4600x^2$	0.9726
Mn		100	4 B	Q***	$y = 126.7696 - 36.9485x + 2.9461x^2$	0.9035
		300		Q*	$y = 131.0333 - 32.5691x - 3.6194x^2$	0.3238
Zn		100	4 C	Q***	$y = 8.3812 - 21.1579x - 1.7807x^2$	0.4440
		300		Q***	$y = 10.4521 + 19.9935x - 1.6403x^2$	0.9474
Cu		100	4 D	L*	$y = 3.0059 - 0.1243x$	0.7607
		300		L*	$y = 0.0650 + 1.3685x$	0.7468
B		100	4 E	Q***	$y = 22.5538 + 2.6050x - 0.2305x^2$	0.4968
		300		L*	$y = 28.7958 + 1.0687x$	0.4879
Al		100	4 F	Q***	$y = 72.5544 - 19.9934x + 1.4860x^2$	0.9436
		300		Q***	$y = 72.9437 - 19.0650x + 1.4128x^2$	0.8166

^zLinear (L) or quadratic (Q) response for N concentration.

^yL ($y = ax + b$) or Q ($y = ax^2 + bx + c$) equations for concentration.

ns, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001.

Table 2. Average plant height, diameter, growth indices (GI), primary shoot caliper (PSC), and total plant dry mass (TDM) of two hibiscus (*Hibiscus hybrid* L. ‘Mocha Moon’ and ‘Starry Starry Night’) cultivars grown at six fertilizer concentrations, harvested at 8 weeks after transplant.

Nitrogen (N) concn (mg·L ⁻¹ N)	Ht ^z (cm)	Diam ^y (cm)	GI ^x (cm)	PSC ^w (mm)	TDM ^v (g)
‘Mocha Moon’					
50	41.9 b ^u	43.0 b	74.3 c	13.0 c	22.1 c
75	54.6 ab	45.9 ab	88.9 bc	15.4 bc	27.8 bc
100	61.0 a	47.1 a	96.9 ab	18.3 ab	31.5 ab
200	67.3 a	52.6 a	106.6 a	18.9 a	34.6 a
300	71.1 a	51.3 a	109.6 a	18.2 ab	36.8 a
400	70.4 a	51.9 a	108.9 a	18.1 ab	32.2 b
Significance	***	**	***	***	***
‘Starry Starry Night’					
50	29.9 d	33.1 c	54.6 c	10.5 d	16.4 c
75	43.6 d	39.0 abc	72.8 b	14.8 c	22.5 b
100	59.5 a	45.7 a	85.7 a	18.9 a	26.8 ab
200	61.8 a	46.1 a	97.4 a	19.3 a	32.3 a
300	63.8 a	42.7 abc	96.1 a	17.3 b	35.6 a
400	63.4 a	36.2 c	90.4 a	17.5 b	31.4 b
Significance	***	**	***	***	***

^zPlant height measured from the substrate surface to the apical meristem.

^yPlant diameter determined by measuring the widest dimension and the axis perpendicular to the widest dimension and averaged.

^xGI = (plant height + plant diameter)/2].

^wPSC determined by measuring below the lowest axillary shoot.

^vTDM = young plant dry mass + plant dry mass.

^uWithin-column means (n = 3) followed by different lower-case letters are significantly different by Tukey’s honestly significant differences test at $P \leq 0.05$.

ns, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Hibiscus 'Mocha Moon'

Fig. 1. Depiction of hibiscus (*Hibiscus hybrid* L. 'Mocha Moon') 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–potassium and a constant level of water-soluble micronutrient blend at 2, 4, 6, and 8 weeks after transplant.

Hibiscus 'Starry Starry Night'

Fig. 2. Depiction of hibiscus (*Hibiscus hybrid* L. 'Starry Starry Night') 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–potassium and a constant level of water-soluble micronutrient blend at 2, 4, 6, and 8 weeks after transplant.

Sufficiency ranges for both *Hibiscus* cultivars were used to determine recommended leaf tissue concentrations of 12 elements by

chronological age. Similar to Papineau and Krug (2014), lower and upper limits of recommended leaf tissue concentration ranges

were defined as the best fit regressions of the pooled data from all *Hibiscus* plants grown at 100–300 mg·L⁻¹ N over an 8-week crop cycle. The nutrient concentrations differed between 'Mocha Moon' and 'Starry Starry Night', but the means were within the established range for each elemental nutrient. To date, no leaf tissue concentration limits are published for *H. hybrid*, but survey measurements taken from greenhouse- and nursery-grown Chinese hibiscus (*Hibiscus rosa-sinensis* L.) and rose of Sharon (*Hibiscus syriacus* L. 'Aphrodite', 'Blue Bird', 'Blushing Bride', 'Collie Mullens', 'Diana', 'Helene', and 'Red Heart') are reported by Bryson and Mills (2014). These tissue concentration ranges will be referred to as the genera *Hibiscus*.

Nitrogen. Total N (NO₃⁻ and NH₄⁻) concentration of *Hibiscus* cultivars in this study harvested at 2, 4, 6, and 8 WAT (Table 3; Fig. 3A) were within a narrower sufficiency range than those previously reported (2.50% to 4.56% N; Bryson and Mills, 2014). At all stages of growth, total N tissue concentration was higher in the plants fertilized with 300 mg·L⁻¹ N than those fertilized with 100 mg·L⁻¹ N (Fig. 3A). At 2 WAT, total N tissue concentration ranged from 3.1% to 5.1% and increased to 5.2% to 5.4% at 6 WAT. These results are consistent with Jeong et al. (2009) which reported increased leaf tissue N concentration of gerbera when fertilized with 100–200 mg·L⁻¹ N from transplant until first open flower (2–8 WAT). Total N tissue concentration of *Hibiscus* decreased to 4.2% to 4.7% at 8 WAT when floral buds were visible. This is similar to Krug et al. (2010) which observed decreased leaf tissue N concentration of flowering zonal geranium 'Tango Dark Red' and 'Rocky Mountain Dark Red' plants fertilized with 100–300 mg·L⁻¹ N at 12 WAT.

Phosphorus. The recommended range for leaf tissue P concentration for the genera *Hibiscus* is between 0.2% and 1.0% (Bryson and Mills, 2014). Leaf tissue P concentration of the *Hibiscus* cultivars in this study is consistent with those previously published. The overall lower and upper limit range increased in a quadratic fashion over time (Fig. 3B), and this trend was also observed in gerbera (Jeong et al., 2009). For plants fertilized with 100 mg·L⁻¹ N, lower optimal P concentrations were 0.30% to 0.45% P at 2 (young growth) to 8 WAT (visible bud), respectively (Table 3; Fig. 3B). For plants fertilized with 300 mg·L⁻¹ N, P concentrations increased from 0.53% to 0.73% P from 2 to 6 WAT, respectively, and then decreased to 0.57% P at visible bud (Table 3; Fig. 3B). At all stages of the crop cycle, P tissue concentration were higher in plants grown at 300 mg·L⁻¹ N than 100 mg·L⁻¹ N and within a narrower range than recommended published ranges by Bryson and Mills (2014).

Potassium. The recommended range for leaf tissue K concentration for the genera *Hibiscus* is between 1.21% and 3.35% (Bryson and Mills, 2014). When plants were fertilized with 100 mg·L⁻¹ N, a quadratic

Table 3. Sufficiency ranges of 12 elemental nutrients determined at 2 (young growth), 4 (active growth), 6 (mature growth), and 8 (visible bud) weeks after transplant (WAT) for two hibiscus (*Hibiscus hybrid* L. ‘Mocha Moon’ and ‘Starry Starry Night’) cultivars (n = 3) grown with 100–300 mg·L⁻¹ nitrogen (N) and recommended leaf tissue for the genera *Hibiscus* as previously published by Bryson and Mills (2014).

		WAT				<i>Hibiscus</i>
Elemental nutrients	Unit of measure	2 (Young growth)	4 (Active growth)	6 (Mature growth)	8 (Visible bud)	Bryson and Mills (2014) ²
Macronutrients						
Total N	%	3.08–5.11	3.59–5.15	5.25–5.42	4.20–4.68	2.50–4.56
Phosphorus		0.30–0.53	0.44–0.70	0.69–0.73	0.45–0.57	0.20–1.00
Potassium		3.17–4.08	3.43–4.15	3.20–3.86	3.02–2.59	1.21–3.35
Calcium		1.60–2.01	2.30–2.67	2.23–2.36	1.76–1.90	1.00–5.18
Magnesium		0.66–0.76	0.77–0.79	0.61–0.81	0.43–0.53	0.25–1.12
Sulfur		0.34–0.45	0.53–0.65	0.52–0.61	0.46–0.38	0.20–0.50
Micronutrients						
Iron	mg·L ⁻¹	79.2–103.5	82.9–122.1	107.6–119.7	75.6–82.9	50–200
Manganese		66.3–82.8	21.1–51.4	16.2–73.1	18.1–99.7	40–289
Zinc		29.0–43.3	41.1–66.0	61.1–69.5	44.7–45.7	20–200
Copper		2.5–3.3	3.3–3.8	6.7–10.2	5.9–10.3	6–50
Boron		27.5–29.8	27.5–29.1	31.7–34.4	28.0–35.6	25–114
Aluminum		39.3–41.8	13.9–15.0	6.9–8.5	9.4–13.7	— ³

²Recommended leaf tissue range for the genera *Hibiscus* previously published by Bryson and Mills (2014).

³No previously reported recommended leaf tissue range for the genera *Hibiscus* by Bryson and Mills (2014).

response was observed where an increase in K concentration occurred between 2 and 4 WAT (young to active growth), and decreased over time from 6 to 8 WAT (maturity to visible bud) (Table 3; Fig. 1C). At 300 mg·L⁻¹ N, K concentration decreased linearly from 4.08% to 2.59% K at 2–8 WAT, respectively (Table 3; Fig. 3C). However, the upper range limit was 21.7%, 23.8%, and 15.2% higher at 2, 4, and 6 WAT than the limit reported by Bryson and Mills (2014), thus broadening the recommended range of leaf tissue K concentration.

Calcium. The recommended range for leaf tissue Ca concentration for the genera *Hibiscus* is between 1.0% and 5.18% (Bryson and Mills, 2014). The previously published Ca concentration range for *Hibiscus* is broader than observed for the cultivars in this study (Table 3). In general, upper and lower Ca leaf concentration range limits followed a quadratic response (Fig. 3D). The measured Ca tissue concentrations were 1.60% to 2.01% Ca at 2 WAT (young growth), increased to 2.30% to 2.67% Ca at 4 WAT (active growth), and then decreased as the plants matured from 6 to 8 WAT. The observed trend is consistent with zonal geranium ‘Rocky Mountain Dark Red’ (Krug et al., 2010), but not osteospermum (Papineau and Krug, 2014) or gerbera (Jeong et al., 2009). Calcium concentration should increase as plants mature (Krug et al., 2010). However, the observed decrease in Ca concentration from 6 to 8 WAT (maturity to visible bud) may be attributed to competitive uptake of K or high relative humidity in the greenhouse thus limiting Ca movement to meristematic tissues (Bryson and Mills, 2014), although no Ca deficiency symptoms were observed. Furthermore, substrate pH ranged from 5.8 to 6.5 which is optimal for *Hibiscus* production and within the optimal range for Ca availability (Dole and Wilkins, 2005).

Magnesium. The recommended range for leaf tissue Mg concentration for the genera *Hibiscus* is between 0.25% and 1.12% (Bryson and Mills, 2014). Similar to Ca, the

previously published Mg concentration range for *Hibiscus* is broader than observed for the cultivars in this study (Table 3). In general, a quadratic response was observed (Fig. 2E). For the lower range limit, tissue Mg concentration increased by 17% from 2 to 4 WAT (young to active growth) and then decreased as the plants matured from 6 WAT onward (Fig. 2E). The upper limit increased steadily from 0.76% to 0.81% Mg from 2 to 6 WAT (young to maturity) and then decreased at 8 WAT (0.53% Mg). Krug et al. (2010) reported a similar trend for the upper range limit of geranium ‘Rocky Mountain Dark Red’ from 2 to 12 WAT. Although within the recommended range, Mg concentrations were significantly lower at 8 WAT and 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.

Sulfur. The recommended range for leaf tissue S concentration for the genera *Hibiscus* is between 0.2% and 0.5% (Bryson and Mills, 2014). Lower and upper limits for the *Hibiscus* cultivars in this study followed a quadratic response over time (Fig. 3F), and were similar to gerbera (Jeong et al., 2009). The sulfur concentrations at 4 and 6 WAT (active growth and maturity) were 0.53% to 0.65% and 0.52% to 0.61% S (Table 3; Fig. 3F), respectively, which were greater than the ranges previously published by Bryson and Mills (2014), thus indicating a broader range limit.

Iron. The recommended range for leaf Fe concentration for the genera *Hibiscus* is between 50 and 200 mg·L⁻¹ (Bryson and Mills, 2014). In general, a quadratic response was observed where Fe concentration at lower and upper limits increased from 2 to 4 WAT and then decreased at 6 WAT onward (Table 3; Fig. 3A). The Fe concentrations were lower and within a narrower range than those published by Bryson and Mills (2014) and ranged from 79.2 to 103.6, 82.9 to 122.1, 107.6 to 119.7, and 75.6 to 82.9 mg·L⁻¹ Fe

at 2, 4, 6, and 8 WAT, respectively. The observed lower range may likely be attributed to the constant rate of micronutrients supplied at each fertilizer concentration and not related to Fe deficiency which is associated with substrate pH > 6.5 because no deficiency symptoms were observed.

Manganese. The recommended range for Mn concentration for the genera *Hibiscus* is between 40 and 289 mg·L⁻¹ Mn (Bryson and Mills, 2014). In the present study, Mn concentration decreased quadratically when plants were fertilized with 100 and 300 mg·L⁻¹ N, but was higher for plants fertilized with 300 than 100 mg·L⁻¹ N (Fig. 4B). Manganese concentrations for plants grown with 100 mg·L⁻¹ N declined from 66.3 to 18.1 mg·L⁻¹ Mn beginning at 2–8 WAT, respectively (Table 3). These values are lower than those previously published (Bryson and Mills, 2014) and plant tissue would be considered Mn deficient. Although Mn concentrations were narrower than previously published ranges, visual symptomology was not observed in either *Hibiscus* cultivars. Increased substrate pH may attribute to the suppressive effect on plant Mn uptake and content or the antagonistic effect of Fe competing for absorption (Bryson and Mills, 2014). The upper optimal ranges for plants grown with 300 mg·L⁻¹ N increased by 20% (16.9 mg·L⁻¹ Mn) at 2–8 WAT. Although the Mn concentration were within a narrower range than previously published ranges, the range became broader as the plants matured (Fig. 4B). This is consistent with trends reported for geranium ‘Tango Dark Red’ (Krug et al. 2010), gerbera (Jeong et al., 2009), and osteospermum cultivars (Papineau and Krug, 2014).

Zinc. The recommended range for Zn concentration for the genera *Hibiscus* is between 20 and 200 mg·L⁻¹ Zn (Bryson and Mills, 2014). Zinc tissue concentrations in the present study were lower and within a narrower range than those previously published for the genera *Hibiscus*. Lower and upper limits followed a quadratic response over time (Fig. 4C), similar to gerbera (Jeong

Fig. 3. Sufficiency ranges of macronutrients [nitrogen (N), phosphorus, potassium, calcium, magnesium, and sulfur] over an 8-week crop cycle in two hibiscus (*Hibiscus hybrid* L. 'Mocha Moon' and 'Starry Starry Night') cultivars grown at 100–300 mg·L⁻¹ N. Measured as the mean $\pm$ SD. Data were pooled over cultivars.

et al., 2009) and osteospermum cultivars (Papineau and Krug, 2014). The lower and upper range limits for Zn tissue concentration increased from 29.0 to 61.1 and 43.3 to 69.5

Fig. 4. Sufficiency ranges of micronutrients (iron, manganese, zinc, copper, boron, and aluminum) over an 8-week crop cycle in two hibiscus (*Hibiscus hybrid* L. 'Mocha Moon' and 'Starry Starry Night') cultivars grown at 100–300 mg·L⁻¹ nitrogen. Measured as the mean $\pm$ SD. Data were pooled over cultivars.

mg·L⁻¹ Zn from 2 and 6 WAT (young to maturity), respectively, and then decreased at 8 WAT (Table 3). Although within the recommended range, lower Zn tissue concentra-

tions observed at 8 WAT may be the result of limited diffusion of available Zn for uptake because of extensive root growth and development. However, uptake earlier in the crop cycle (at 4–6 WAT) was not limited. Furthermore, Bryson and Mills (2014) indicated that high levels of available P and Fe in soils also adversely affects plant uptake of Zn, which may attribute to lower concentrations observed at 8 WAT.

Copper. The recommended range for Cu concentration for the genera *Hibiscus* is between 6 and 50 mg·L⁻¹ Cu (Bryson and Mills, 2014). Over time, Cu tissue concentration increased linearly (Fig. 4D). Copper concentrations of plants fertilized with 100–300 mg·L⁻¹ N were 2.5–3.3 and 3.3–3.8 mg·L⁻¹ Cu at 2–4 WAT (Table 3), respectively, and were lower than those previously published for the genera *Hibiscus*. However, Cu deficiency is uncommon in greenhouse production (Jeong et al., 2009) and no deficiency symptoms were observed. Copper deficient plant tissue may be attributed to the dilution effect caused by plant growth following N fertilization (Bryson and Mills, 2014), although average GI of plants fertilized with 100–300 mg·L⁻¹ N at 2 and 4 WAT were 15.7–16.9 and 24.4–29.4 cm, respectively, and not statistically different (data not shown).

Boron. The recommended range for B concentration for the genera *Hibiscus* is between 25 and 114 mg·L⁻¹ B (Bryson and Mills, 2014). When plants were fertilized with 100 mg·L⁻¹ N, a quadratic response was observed where a slight increase in B concentration occurred from 2 to 6 WAT (young to maturity), and decreased at 8 WAT (visible bud) (Table 3; Fig. 4E). At 300 mg·L⁻¹ N, B concentration increased linearly from 29.8% to 35.6% mg·L⁻¹ B at 2–8 WAT, respectively (Table 3; Fig. 4E). Boron tissue concentrations in this study provide a narrower range limit than values reported by Bryson and Mills (2014).

Aluminum. To date, no recommended range for Al concentration for the genera *Hibiscus* exists over time. The present study establishes an optimal concentration range overtime where tissue concentration decreased in a quadratic fashion (Fig. 4F). Aluminum concentrations of plants fertilized with 100–300 mg·L⁻¹ N were 39.3–41.8 mg·L⁻¹ at 2 WAT and decreased to 9.4–13.7 mg·L⁻¹ at 8 WAT (Table 3). Although not an essential element (Bryson and Mills, 2014), Morgan (2000) describes Al as a new beneficial element for plants which may influence root activity for P uptake. Based on these findings and the statement by Morgan (2000), it is postulated that the observed decreasing Al concentrations from 2 to 8 WAT may contribute to increased root activity and thus, increased concentration of P in leaves from 2 to 8 WAT.

Conclusion

Collectively, the results from this study establish an optimum fertilizer concentration of 100–300 mg·L⁻¹ N and more precise leaf

tissue sufficiency ranges for *H. hybrid*. This study expands the general understanding of leaf tissue nutrient sufficiency ranges by chronological age. An overall trend of increasing tissue concentration over time was observed for N, P, Ca, S, Zn, Cu, and B, although a decreasing trend was observed for K, Fe, Mn, and Al. The leaf tissue concentration sufficiency ranges determined in this study are narrower than those reported by Bryson and Mills (2014) and likely because of investigating only two cultivars. Therefore, further experiments including more than two cultivars of *Hibiscus* and other fertilizer sources is warranted. Furthermore, continued research to establish nutrient sufficiency ranges by chronological age of other popular herbaceous perennial species grown in soilless substrates during container production is needed.

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