

Effects of Nutrient Solution Concentration and Daily Light Integral on Growth and Nutrient Concentration of Several Basil Species in Hydroponic Production

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Abstract. Our objective was to quantify the effect of mineral nutrient concentration of a nutrient solution on the growth of basil species and cultivars grown under high and low photosynthetic daily light integrals (DLIs). Sweet basil (*Ocimum basilicum* ‘Nufar’), lemon basil (*O. ×citriodorum* ‘Lime’), and holy basil (*O. tenuiflorum* ‘Holy’) seedlings were transplanted into nutrient-film technique (NFT) systems with different nutrient solution electrical conductivities (EC; 0.5, 1.0, 2.0, 3.0, or 4.0 dS·m⁻¹) in greenhouses with a low (≈7 mol·m⁻²·d⁻¹) or high (≈15 mol·m⁻²·d⁻¹) DLI. Although nutrient solution EC did not affect growth and morphology, increasing DLI did. For example, when sweet basil was grown under a high DLI, the fresh and dry weight, height, and node number increased by 144%, 178%, 20%, and 18%, respectively, compared with plants grown under the low DLI, and branching was also stimulated. In contrast, DLI had little effect on tissue nutrient concentration, although nutrient solution did. Most tissue nutrient concentrations increased with increasing EC, with the exception of Mg and Ca. For example, N in sweet basil increased by 0.6% to 0.7% whereas Mg decreased by 0.2% as EC increased from 0.5 to 4.0 dS·m⁻¹. Across treatments and basil species, tissue nutrient concentrations were generally within recommended ranges with no visible deficiencies. Based on our results, nutrient solution concentrations for hydroponic basil production can be selected based on factors such as other species grown in the same solution or by reducing fertilizer inputs.

Basil is a popular fresh culinary herb commonly produced outdoors (Jensen, 2002; Simon et al., 1999). With the demand for fresh basil, year-round production in temperate climates is only possible in controlled environments (Succop, 1998; Wolf et al., 2005). In controlled environments such as greenhouses, hydroponic systems are commonly used to produce basil (Hochmuth and Cantliffe, 2012; Walters and Currey, 2015).

Nutrient solutions can influence growth, appearance, nutritional value, and shelf life of basil (De Pascale et al., 2006). For example, research on outdoor field or containerized

greenhouse production of basil has demonstrated that increasing N fertilization increases shoot mass (Biesiada and Kuś, 2010; Golcz et al., 2006; Nurzynska-Wierdak et al., 2012; Sifola and Barbieri, 2006). However, commercial hydroponic producers commonly adjust nutrient solutions based on nutrient solution EC, which reflects the total concentration of fertilizer salts in solution, rather than specific nutrients such as N (Resh, 2013). We have found few reports on the effect of recirculating hydroponic nutrient solution EC and growth of basil species. Researchers found growth of different basil types grown over a 4- to 5-month period is influenced by EC (Suh and Park 1997); however, this exceeds the 5-week production time common commercially.

In addition to mineral nutrients, photosynthetically active radiation affects growth and development of crops grown in greenhouses and controlled environments. For basil and in many other culinary herbs, fresh and dry weight increases as DLI increases to a certain point (Beaman et al., 2009; Currey et al., 2017; Litvin and Currey, 2017). The ambient DLI varies over the course of the year and is at seasonally low levels during the fall, winter, and spring (Korczynski et al.,

2002). Supplemental lighting may be used in greenhouses when the ambient DLI is low to increase herb growth and reduce production times (Currey et al., 2017; Fisher et al., 2017).

Some hydroponic producers adjust their nutrient solution between winter and summer, using a lower EC during the summer when both light intensity and air temperatures in the greenhouse are greater compared with the winter (Morgan, 2005). It is unclear how increasing light alone affects nutrient solution EC requirements, as would be the case for a producer using supplemental light during the fall, winter, and spring, when air temperatures in the greenhouse are more easily controlled. We have found no peer-reviewed research quantifying the effect of nutrient solution used in hydroponic basil production on plant growth and tissue nutrient concentrations under different DLIs. Therefore, the objectives of our research were to quantify the effect of nutrient solution concentration on growth and tissue nutrient concentrations of three basil species grown under low and high DLIs.

Materials and Methods

Plant material and propagation. Three basil species were selected: sweet (Johnny’s Selected Seeds, Fairfield, ME), lemon (Johnny’s Selected Seeds), and holy (Seeds of Change, Dominguez, CA) basil. Cultivars were selected to represent a range of different basil genotypes and phenotypes based on results from Walters and Currey (2015). Phenolic-foam 162-cell propagation cubes (Oasis® Horticultures® XL Multiseed; Smithers-Oasis, Kent, OH) were placed in a plastic flat (25 cm wide × 50 cm long), hydrated with reverse-osmosis (RO) water, and allowed to drain. Two seeds were sown per cell and flats were placed in an environmental growth chamber (E-41L; Percival Scientific, Perry, IA) with an air temperature of 22.9 ± 0.7 °C measured every 15 s with a naturally aspirated temperature sensor (TMC1-HD; Onset Computer Corporation, Bourne, MA) in a solar radiation shield (RS3; Onset Computer Corporation). A photosynthetic photon flux (PPF) of 378 ± 8 μmol·m⁻²·s⁻¹ was provided by fluorescent lamps for 16 h per day and measured every 15 s with an amplified quantum sensor (SQ-222; Apogee Instruments, Logan, UT). Average light intensities and air temperatures were logged every 15 min by a data logger (HOBO U12; Onset Computer Corporation). Seeds were irrigated once daily with RO water until radical emergence, after which seedlings were irrigated daily with RO water supplemented with 100 mg·L⁻¹ N provided from a complete, balanced, water-soluble fertilizer (Jack’s Hydro FeED 16N–1.8P–14.3K; JR Peters Inc., Allentown, PA).

Hydroponic systems. On 21 Oct., 24 Nov., and 30 Dec. 2014 (2 weeks after sowing), seedlings were thinned to one seedling per cell and transplanted into NFT hydroponic systems. Each NFT system consisted of troughs that were 10 cm wide, 5 cm tall,

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and 203 cm long (GT50-612; FarmTek, Dyersville, IA), with a 3% slope. Nutrient solution was held in a 151-L reservoir (Premium Reservoir; Botanicare, Chandler, AZ) delivered to troughs by a submersible water pump (Active Aqua 33 Watt pump; Hydrofarm, Grand Prairie, TX), resulting in a flow of ≈ 1 L·min⁻¹ per trough. Plants were placed in 3.5-cm-diameter holes cut into the top of the NFT troughs, allowing the base of the phenolic foam to rest on the bottom of the trough.

Greenhouse environment and DLI treatments. Five hydroponic systems were in each of two independent glass-glazed greenhouses (Ames, IA; lat. 42.0°N). Radiant hot-water heating and fog cooling were used to maintain an average daily temperature of 21 ± 1 °C, with actual temperatures reported in Table 1. The target DLI for the low and high DLI treatments was 7 or 15 mol·m⁻²·d⁻¹, respectively (Table 1). A supplemental PPF of 180 ± 27 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ from high-pressure sodium lamps (PL 3000; P.L. Light Systems, Beamsville, ON, Canada) was provided between 0600 HR and 2200 HR to maintain 16-h photoperiods in both DLI treatments. However, between these times, high-pressure sodium (HPS) lamps turned off when outdoor instantaneous light intensity decreased to certain set points for more than 15 min; the shutoff set point for the high DLI treatment was greater than the low DLI treatment. To maintain target

DLIs within and across replications in time, set points changed as outdoor ambient PPF and daylength changed. Aluminized shade cloth (XLS 15 Revolux; Ludvig Svensson, Kinna, Sweden) was also used in the low DLI house to decrease ambient light intensity midday to maintain the target DLI for later replications. Shade curtains, HPS lamps, heating, and cooling were controlled with an environmental control system (ARGUS Titan; ARGUS Control Systems LTD., Surrey, BC, Canada).

The air temperature was measured every 15 s by four temperature probes (41342; R.M. Young Company, Traverse City, MI) in an aspirated radiation shield (43502; R.M. Young Company), and the PPF was measured every 15 s by eight quantum sensors (LI-190SL; LI-COR Biosciences, Lincoln, NE) per greenhouse. Temperature probes and quantum sensors were connected to a data logger (CR1000 Measurement and Control System; Campbell Scientific, Logan, UT), with mean values logged every 15 min.

Nutrient solutions. The nutrient solutions consisted of RO water, MgSO₄·7H₂O, and 16N-1.8P-14.3K fertilizer (Jack's Hydro FeED; JR Peters Inc.; Table 2), with a target N:Mg of 5:1. The pH was measured daily with a pH probe (HI 981504 pH/TDS/Temperature Monitor; Hanna Instruments, Woonsocket, RI) and adjusted to 6.0 using potassium carbonate (pH Up; General Hydroponics,

Sebastopol, CA) and a combination of phosphoric and citric acids (pH Down; General Hydroponics). EC was measured with a handheld meter (HI 9813-6 Portable pH/EC/TDS Meter; Hanna Instruments) and adjusted to 0.5, 1.0, 2.0, 3.0, or 4.0 dS·m⁻¹ daily using RO water or concentrated 16N-1.8P-14.3K fertilizer. The solution was aerated constantly with four 15-cm-long air stones (Active Aqua air stone; Hydrofarm) per system attached to a 110-L air pump (Active Aqua commercial air pump; Hydrofarm). Oxygen concentrations (8.3 ± 0.2 ppm) in the nutrient solutions were measured daily with a dissolved oxygen meter (HI 9147; Hanna Instruments). Nutrient solutions were circulated continuously through a heater/chiller unit (SeaChill TR-10; TECO, Terrell, TX) to maintain a water temperature of 22.1 ± 0.5 °C.

Data collection and calculation. Nutrient solution samples were collected from each system before transplanting and after harvesting to determine initial and final nutrient concentrations. Nitrogen was measured with a flow-injection analyzer (QuickChem 8500; Lachat Instruments, Loveland, CO). Phosphorus, K, Mg, Ca, S, Zn, Mn, Cu, Fe, and B were analyzed by inductively coupled plasma-optical emission spectroscopy (Optima 4300 DV; Perkin Elmer, Waltham, MA).

Three weeks after transplanting, relative chlorophyll concentration was measured with a handheld soil-plant analysis development (SPAD) meter (SPAD-502; Konica Minolta, Ramsey, NJ) on the second-most mature leaf, the newest fully expanded leaf, and a leaf midway between those points for five plants per treatment per replication. Height of the main stem, and node and branch (>2.5 cm) numbers were recorded. Plants were severed at the surface of the substrate and fresh weight was recorded immediately. Shoots were rinsed in RO water three times, placed in a forced-air oven maintained at 67 °C for 3 d, then weighed, and dry weight was recorded.

Table 1. Average (mean \pm SD) daily light integral (DLI) and air temperature for hydroponic basil grown in nutrient-film technique hydroponic systems with a range of nutrient solution electrical conductivities (ECs; 0.5–4.0 dS·m⁻¹) in a greenhouse under a low (≈ 7 mol·m⁻²·d⁻¹) or high (≈ 15 mol·m⁻²·d⁻¹) daily light integral (DLI) for 3 weeks.

Replication	Target DLI (mol·m ⁻² ·d ⁻¹)	Actual DLI (mol·m ⁻² ·d)	Air temp (°C)
1	7.0	6.7 \pm 0.8	21.8 \pm 0.3
	15.0	14.5 \pm 1.6	21.8 \pm 0.2
2	7.0	6.6 \pm 0.9	22.0 \pm 0.3
	15.0	14.9 \pm 1.2	21.6 \pm 0.4
3	7.0	7.4 \pm 1.1	21.4 \pm 0.4
	15.0	15.7 \pm 1.4	21.8 \pm 0.3

Table 2. Nutrient concentrations of hydroponic nutrient solutions with electrical conductivities (ECs) ranging from 0.5 to 4.0 dS·m⁻¹ for basil grown in hydroponic systems under low (≈ 7.0 mol·m⁻²·d⁻¹) or high (≈ 15.0 mol·m⁻²·d⁻¹) daily light integrals (DLIs) at the beginning of the experiment, and the change (Δ) in concentration from the beginning to the end of the experiment (3 weeks).

Target DLIs	EC	Time	Nutrient concn (mg·L ⁻¹)											
			N	P	K	Mg	Ca	S	Zn	Mn	Cu	Fe	B	
Low	0.5	Initial	56	26	41	13	17	31	0.2	0.05	0.04	0.7	0.1	
		Δ	-11	+1	+35	-2	-3	-4	-0.04	-0.003	-0.007	-0.04	+0.003	
	1.0	Initial	118	52	94	25	32	63	0.4	0.4	0.1	1.6	0.2	
		Δ	-16	-2	+75	-2	-3	-6	-0.03	-0.2	-0.01	-0.03	0	
	2.0	Initial	254	93	198	51	67	112	0.8	0.8	0.2	3.4	0.4	
		Δ	-16	-6	+120	-2	-3	-5	-0.01	-0.05	-0.01	0.09	+0.01	
	3.0	Initial	412	149	302	80	108	178	1.3	1.3	0.3	5.5	0.6	
		Δ	-11	-4	+55	-3	-9	-12	-0.04	-0.07	+0.003	-0.3	-0.01	
	4.0	Initial	534	200	401	107	140	238	1.7	1.6	0.4	6.9	0.7	
		Δ	-22	-5	+141	-2	-4	-11	-0.01	-0.2	+0.003	+0.1	+0.003	
	High	0.5	Initial	57	29	50	14	17	33	0.2	0.1	0.05	0.8	0.1
			Δ	-26	+3	+8	-5	-7	-11	-0.05	-0.1	-0.01	-0.08	+0.01
1.0		Initial	113	46	94	25	30	57	0.4	0.2	0.1	1.6	0.2	
		Δ	-38	-4	+45	-7	-9	-14	-0.05	-0.06	-0.02	-0.2	0	
2.0		Initial	247	96	190	53	63	120	0.8	0.7	0.2	3.3	0.4	
		Δ	-41	-24	+35	-4	-5	-14	-0.03	-0.05	-0.003	-0.02	0	
3.0		Initial	394	152	348	78	96	178	1.4	1.4	0.4	5.9	0.6	
		Δ	-61	-36	+119	-6	-7	-16	-0.1	-0.08	-0.02	-0.4	-0.02	
4.0		Initial	573	194	475	104	134	230	2.0	2.0	0.5	8.3	0.8	
		Δ	-88	-24	+111	-11	-4	-43	-0.05	-0.10	-0.02	-0.4	-0.01	

Table 3. Analysis of variance for fresh and dry weight, height, node number, branch number, soil-plant analysis development (SPAD) meter index, and nutrient concentrations for sweet basil (*Ocimum basilicum* 'Nufar'), lemon basil (*Ocimum ×citriodorum* 'Lime'), and holy basil (*Ocimum tenuiflorum* 'Holy') 3 weeks after transplanting into nutrient-film technique hydroponic systems with a range of nutrient solution electrical conductivities (EC; 0.5–4.0 dS·m⁻¹) in a greenhouse under a low (≈ 7 mol·m⁻²·d⁻¹) or high (≈ 15 mol·m⁻²·d⁻¹) daily light integral (DLI).

Parameter	Sweet basil			Lemon basil			Holy basil		
	EC	DLI	EC × DLI	EC	DLI	EC × DLI	EC	DLI	EC × DLI
Fresh weight (g)	NS	***	NS	NS	***	NS	NS	***	NS
Dry weight (g)	NS	***	NS	NS	***	NS	NS	***	NS
Height (cm)	NS	***	NS	NS	*	NS	NS	***	NS
Node (no.)	NS	***	NS	NS	***	NS	NS	***	NS
Branch (no.)	NS	***	NS	NS	***	NS	NS	***	NS
SPAD	***	***	NS	*	***	NS	***	***	NS
N (%)	***	***	NS	***	NS	NS	***	*	NS
P (%)	***	NS	NS	***	NS	NS	**	*	NS
K (%)	*	NS	NS	NS	**	NS	NS	**	NS
Mg (%)	***	NS	NS	***	NS	NS	***	*	NS
Ca (%)	***	**	NS	***	NS	NS	***	NS	NS
S (%)	***	NS	NS	***	NS	NS	NS	**	NS
Zn (mg·kg ⁻¹)	NS	***	NS	*	NS	NS	***	NS	NS
Mn (mg·kg ⁻¹)	NS	*	NS	NS	*	NS	NS	NS	NS
Cu (mg·kg ⁻¹)	*	***	NS	***	***	NS	*	***	NS
Fe (mg·kg ⁻¹)	NS	*	NS	NS	NS	NS	NS	NS	NS
B (mg·kg ⁻¹)	**	**	NS	**	**	NS	NS	*	NS

*, **, or *** indicate significance at $P \leq 0.05$, 0.01, or 0.001, respectively. NS = nonsignificant.

Table 4. Fresh and dry weight, height, node number, branch number, and soil-plant analysis development (SPAD) meter index for sweet basil (*Ocimum basilicum* 'Nufar'), lemon basil (*Ocimum ×citriodorum* 'Lime'), and holy basil (*Ocimum tenuiflorum* 'Holy') 3 weeks after transplanting into nutrient-film technique hydroponic systems in a greenhouse under a high (≈ 15 mol·m⁻²·d⁻¹) or low (≈ 7 mol·m⁻²·d⁻¹) daily light integral (DLI). Data were pooled across electrical conductivities within DLI for each species. Each value represents the mean of three replications.

Parameter	DLI		Sig.
	Low	High	
Sweet basil			
Fresh weight (g)	12.5	30.5	***
Dry weight (g)	0.9	2.5	***
Height (cm)	13.2	15.9	***
Nodes (no.)	4.3	5.1	***
Branches (no.)	0.0	2.3	***
SPAD	25.7	34.1	***
Lemon basil			
Fresh weight (g)	6.2	18.9	***
Dry weight (g)	0.5	1.9	***
Height (cm)	16.3	18.5	*
Nodes (no.)	5.5	6.3	***
Branches (no.)	3.5	7.5	***
SPAD	30.1	40.2	***
Holy basil			
Fresh weight (g)	6.4	19.7	***
Dry weight (g)	0.5	1.8	***
Height (cm)	14.1	17.8	***
Nodes (no.)	5.7	6.3	***
Branches (no.)	2.5	7.3	***
SPAD	32.8	39.9	***

* or *** indicate significance (Sig.) at $P \leq 0.05$ or 0.001, respectively. Each value represents the mean of three replications.

Dried shoot tissue was analyzed to determine nutrient concentrations. Determination of Kjeldahl nitrogen for all tissue samples began with standard digestion in concentrated sulfuric acid at 360 °C for ≈ 1.5 h using a Tecator 40 block digester. The resultant ammonium fraction was measured with a flow-injection analyzer (QuickChem

Table 5. Nutrient concentrations of sweet basil (*Ocimum basilicum* 'Nufar'), lemon basil (*Ocimum ×citriodorum* 'Lime'), and holy basil (*Ocimum tenuiflorum* 'Holy') affected by a high (≈ 15 mol·m⁻²·d⁻¹) or low (≈ 7 mol·m⁻²·d⁻¹) daily light integral (DLI) 21 d after transplanting into nutrient-film technique hydroponic systems. Data were pooled across electrical conductivities within DLI for each species.

Nutrient concn	DLI		Sig.
	Low	High	
Sweet basil			
N (%)	5.4	5.1	*
K (%)	7.0	6.5	*
Ca (%)	1.5	1.4	*
Zn (ppm)	123	103	**
Mn (ppm)	213	185	**
Cu (ppm)	18	15	**
Fe (ppm)	135	116	*
B (ppm)	42	35	**
Lemon basil			
K (%)	5.1	4.6	**
Mn (ppm)	185	158	*
Cu (ppm)	15	12	***
B (ppm)	39	34	**
Holy basil			
N (%)	6.0	6.2	*
P (%)	1.6	1.4	*
K (%)	5.2	4.7	**
S (%)	0.55	0.62	**
Mn (ppm)	187	166	*
Cu (ppm)	17	14	***
B (ppm)	37	33	**

*, **, or *** indicate significance (Sig.) at $P \leq 0.05$, 0.01, or 0.001, respectively. Each value represents the mean of three replications.

8500; Lachat Instruments) using a buffered salicylate–hypochlorite solution for color development. Determination of P, K, Ca, Mg, S, Zn, Mn, Cu, Fe, and B in all tissue samples began with initial digestion in concentrated nitric acid at 90 °C followed by three small additions of 30% hydrogen peroxide, with a total time for digestion of ≈ 1 h. Digested samples were filtered and analyzed by inductively coupled

plasma–optical emission spectroscopy (Optima 4300 DV; Perkin Elmer).

Experimental design and statistical analyses. For each species, the experiment was organized in a randomized complete block design with a factorial arrangement. The factors included nutrient solution concentrations (five concentrations) and DLIs (two DLIs) with 10 plants of each species per individual NFT system per replication. The experiment was replicated three times over time.

Analyses of variance and t tests with $\alpha = 0.05$ were performed using JMP Version 11 (SAS Institute Inc., Cary, NC); regression analyses were performed using Sigma Plot 13.0 (Systat Software, San Jose, CA). To analyze the main effect of EC, data were pooled across DLI within EC for each species, and regression analyses were performed. To analyze the main effect of DLI, data were pooled across EC within DLI for each species, and t tests were performed across DLI.

Results

Nutrient solutions. Specific mineral nutrient concentrations changed from the beginning to the end of the experiment (Table 2). Concentrations of N and S changed less in hydroponic systems in low DLI treatments than those in high DLI treatments. For example, solution N in low DLI treatments decreased by 11 to 22 mg·L⁻¹ whereas concentrations in high DLI treatments decreased by 26 to 88 mg·L⁻¹ from transplant to harvest. From the beginning to the end of the experiment, solution S changed with EC and DLI. Under low DLI conditions, S concentrations decreased by 4 to 12 mg·L⁻¹ whereas under high DLI treatments, concentrations decreased by 11 to 43 mg·L⁻¹. As EC increased from 0.5 to 4.0 dS·m⁻¹, S concentration decreased by 7 to 32 mg·L⁻¹ from the beginning to end of the experiment. The change in

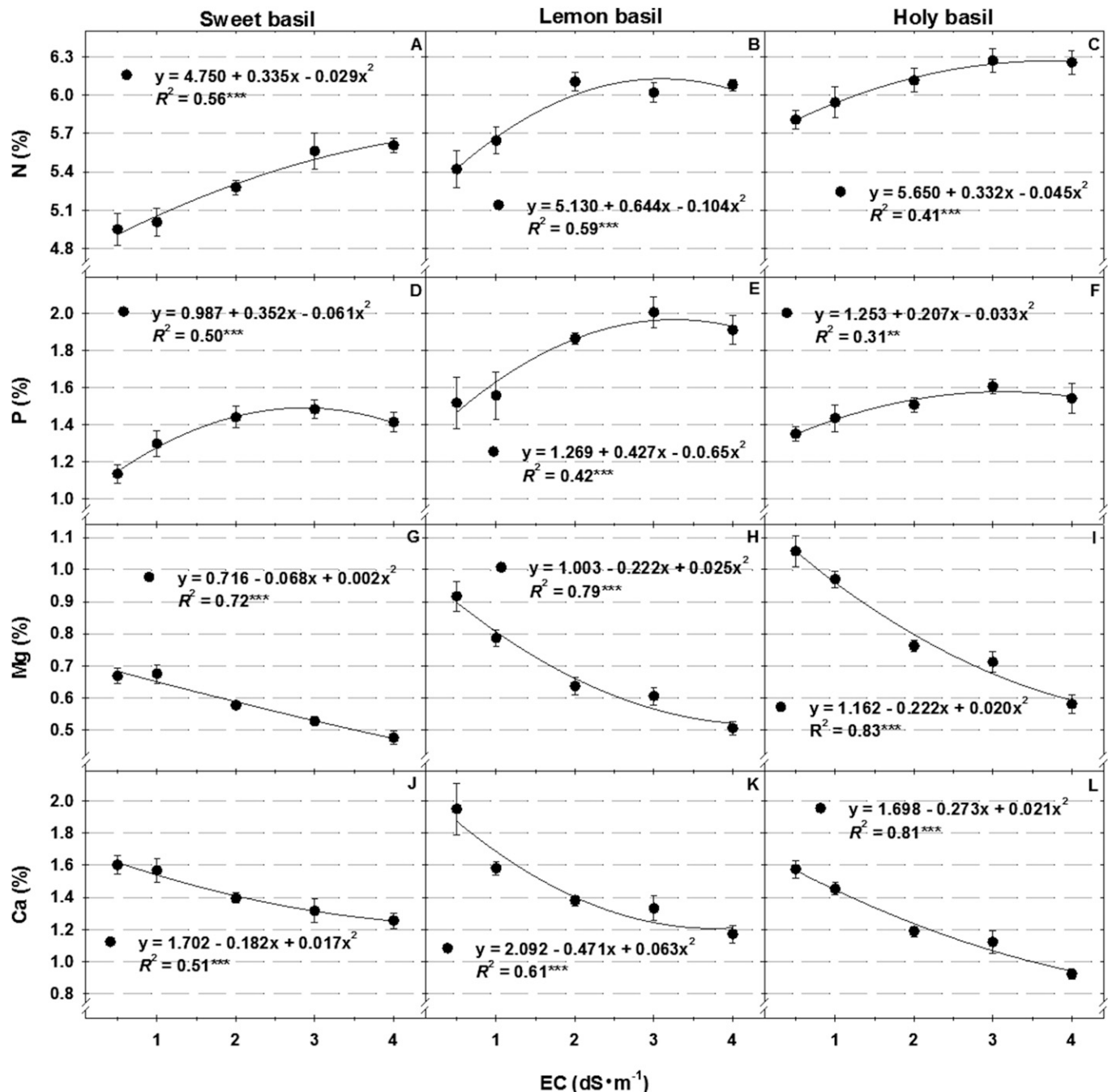


Fig. 1. (A–L) Tissue nitrogen (N), phosphorus (P), magnesium (Mg), and calcium (Ca) concentrations of sweet basil (*Ocimum basilicum* ‘Nufar’), lemon basil (*O. citriodorum* ‘Lime’), and holy basil (*O. tenuiflorum* ‘Holy’) 3 weeks after transplanting into nutrient-film technique hydroponic systems containing nutrient solutions with 0.5, 1.0, 2.0, 3.0, or 4.0 $\text{dS}\cdot\text{m}^{-1}$ electrical conductivities (ECs). Data were pooled across daily light integrals with EC. Each symbol represents the mean of six replications with 10 plants per replicate, and error bars represent the SES of the mean of the six replicates. ** or *** indicate significance at $P \leq 0.01$ or 0.001 , respectively.

concentration of other nutrients analyzed was unaffected by DLI or EC. The N, P, Mg, Ca, S, Zn, and Mn concentrations decreased whereas K concentrations increased by 8 to $118 \text{ mg}\cdot\text{L}^{-1}$ and by 35 to $141 \text{ mg}\cdot\text{L}^{-1}$ under high and low DLI treatments, respectively.

Sweet basil. Plant growth of sweet basil was influenced by DLI, but not nutrient solution EC (Table 3). For example, fresh and dry weight, height, node number, branch number, and SPAD increased as DLI increased (Table 4). Sweet basil tissue N, K,

Ca, Zn, Mn, Cu, Fe, and B concentrations decreased as DLI increased, whereas P, Mg, and S concentrations were unaffected by DLI (Table 5).

Nutrient solution EC affected tissue N, P, K, Mg, Ca, S, Cu, and B concentrations, but not Zn, Mn, or Fe concentrations (Table 3). Sweet basil tissue N concentration increased by 0.7% as EC increased from 0.5 to $4.0 \text{ dS}\cdot\text{m}^{-1}$ (Fig. 1). Tissue P, S, and Cu concentrations increased by 0.3%, 0.1%, and $4 \text{ mg}\cdot\text{kg}^{-1}$, respectively, as EC increased

from 0.5 to $3.0 \text{ dS}\cdot\text{m}^{-1}$ (Figs. 1 and 2). As EC increased from 1.0 to $4.0 \text{ dS}\cdot\text{m}^{-1}$, tissue K concentration decreased by 1.3% whereas B concentration increased by $10 \text{ mg}\cdot\text{kg}^{-1}$ (Fig. 2). Tissue Mg and Ca concentrations decreased by 0.2% and 0.3%, respectively (Fig. 1), as EC increased from 0.5 to $4.0 \text{ dS}\cdot\text{m}^{-1}$.

Lemon basil. Lemon basil growth was unaffected by EC, but was affected by DLI (Table 3). Fresh weight increased by 12.7 g (205%) whereas dry weight increased by

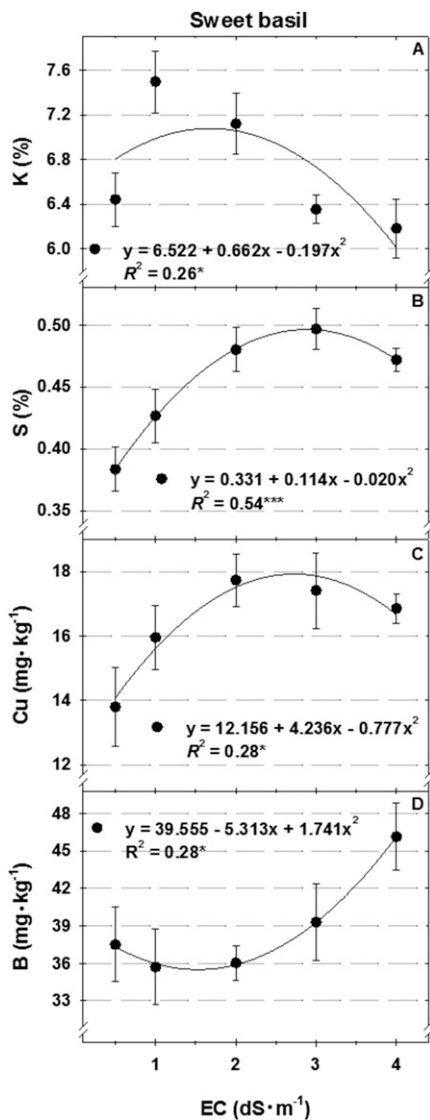


Fig. 2. (A–D) Tissue potassium (K), sulfur (S), copper (Cu), and boron (B) concentrations of sweet basil (*Ocimum basilicum* ‘Nufar’) 3 weeks after transplanting into nutrient-film technique hydroponic systems containing nutrient solutions with 0.5, 1.0, 2.0, 3.0, or 4.0 dS·m⁻¹ electrical conductivities (ECs). Data were pooled across daily light integrals with EC. Each symbol represents the mean of six replications with 10 plants per replicate, and error bars represent the SEs of the mean of the six replicates. * or *** indicate significance at $P \leq 0.05$ or 0.001, respectively.

1.4 g (280%) with increasing DLI (Table 4). Plants grown under a high DLI were 2.2 cm taller, with 4.0 more branches, 0.8 more nodes, and a 10.1 greater SPAD index. Increasing DLI decreased K, Mn, Cu, and B lemon basil tissue concentrations by 0.5%, 27 mg·kg⁻¹, 3 mg·kg⁻¹, and 5 mg·kg⁻¹, respectively, but did not affect other tissue nutrient concentrations (Table 5).

Tissue N, P, Mg, Ca, S, Zn, Cu, and B concentrations were affected by nutrient solution EC, but K, Mn, and Fe were not (Table 3). For example, as EC increased from 0.5 to 2.0 or 3.0 dS·m⁻¹, tissue N, P, S, and Cu

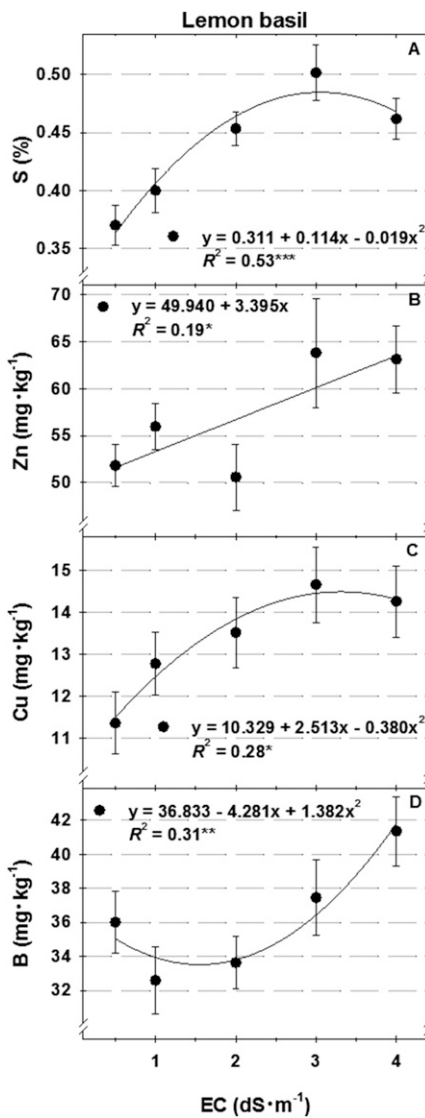


Fig. 3. (A–D) Tissue S, Zn, Cu, and B concentrations of lemon basil (*Ocimum ×citriodorum* ‘Lime’) 3 weeks after transplanting into nutrient-film technique hydroponic systems containing nutrient solutions with 0.5, 1.0, 2.0, 3.0, or 4.0 dS·m⁻¹ electrical conductivities (ECs). Data were pooled across daily light integrals with EC. Each symbol represents the mean of six replications with 10 plants per replicate, and error bars represent the SEs of the mean of the six replicates. *, **, or *** indicate significance at $P \leq 0.05$, 0.01, or 0.001, respectively.

concentrations increased (Figs. 1 and 3). Lemon basil Zn and B concentrations increased as EC increased from 0.5 and 1.0 to 4.0 dS·m⁻¹, respectively, whereas Mg and Ca concentrations decreased as EC increased from 0.5 to 4.0 dS·m⁻¹ (Fig. 3).

Holy basil. Nutrient solution EC did not influence holy basil growth, but DLI did (Table 3). Holy basil grown under high DLI had 13.3 g more fresh weight, 1.3 g more dry weight, and were 3.7 cm taller (Table 4) compared with plants grown under the low DLI. Branch and node numbers increased by 4.8 and 0.6, respectively, as DLI increased,

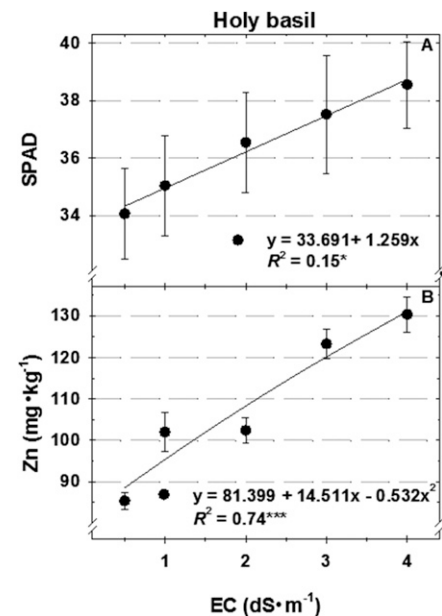


Fig. 4. (A, B) Soil-plant analysis development (SPAD) meter index and tissue Zn concentrations of holy basil (*Ocimum tenuiflorum* ‘Holy’) 3 weeks after transplanting into nutrient-film technique hydroponic systems containing nutrient solutions with 0.5, 1.0, 2.0, 3.0, or 4.0 dS·m⁻¹ electrical conductivities (ECs). Data were pooled across daily light integrals with EC. Each symbol represents the mean of six replications with 10 plants per replicate, and error bars represent the SEs of the mean of the six replicates. * or *** indicates significance at $P \leq 0.05$ or 0.001, respectively.

whereas SPAD index increased by 7.1. As DLI increased, tissue P, K, Mn, Cu, and B concentrations in holy basil decreased, whereas tissue N and S concentrations increased (Table 5). SPAD increased by 4.5 (Fig. 4) with increasing EC (0.5–4.0 dS·m⁻¹). As EC increased from 0.5 to 3.0 dS·m⁻¹, holy basil tissue N and P increased (Fig. 1), and Zn concentrations increased as EC further increased up to 4.0 dS·m⁻¹ (Fig. 4), whereas Mg and Ca concentrations decreased by 0.5% and 0.6%, respectively (Fig. 1). Tissue concentrations of other nutrients were unaffected by EC.

Discussion

Nutrient solution EC had no effect on growth and development of all three basil species, although DLI did. In contrast to our findings, Suh and Park (1997) conducted an experiment to determine the optimal hydroponic nutrient solution EC for sweet, opal, and bush basil and found fresh weight was affected by EC. In their results, sweet basil fresh weight increased from 148 to 329 g as the EC decreased from three times the base solution to one-half times the base solution. Their results may differ as a result of a longer production time (≈8.5 weeks) compared with that of a commercial producer (3–4 weeks). This lack of EC effect on mass also contrasts with previous field and container research that found an increase in shoot mass with

increased N fertilization (Biesiada and Kuś, 2010; Golez et al., 2006; Nurzynska-Wierdak et al., 2012; Sifola and Barbieri, 2006). This may be attributed to constant nutrient availability in recirculating hydroponic production in which the EC of nutrient solutions is maintained constantly compared with field and container production, which receive intermittent fertilizer and water applications and have varying substrate and soil moisture levels. We found no change in height or branching in response to nutrient solution EC; however, increasing N fertilization has been reported to have mixed effects on height and branching in basil. For example, Nurzynska-Wierdak et al. (2012) reported that the height of sweet basil 'Wala' decreased by 6 cm and branching increased by 0.5 branch as N increased from 0.2 to 0.9 kg·m⁻³ of substrate. However, similar to our findings, Sifola and Barbieri (2006) described increasing N had no effect on height for field-grown sweet basil.

The effect of DLI on fresh and dry weight for the three basil species is consistent with previous research on sweet basil (Beaman et al., 2009; Chang et al., 2008). Dry weight of basil grown by Chang et al. (2008) increased as DLI increased from 5.3 to 24.9 mol·m⁻²·d⁻¹ whereas Beaman et al. (2009) reported edible biomass of 'Genovese', 'Italian Large Leaf', and 'Nufar' sweet basil was greatest under a PPF of 500 μmol·m⁻²·s⁻¹ (28.8 mol·m⁻²·d⁻¹). Consistent with Chang et al. (2008), who reported increasing DLI by 19.6 mol·m⁻²·d⁻¹ increased branching by 2.5 branches per plant, branching of basil increased with DLI in our study. Increasing DLI resulted in a greater SPAD index for sweet, holy, and lemon basil, and our results on increasing DLI agree with those of Fukuda et al. (2002), in which the use of supplemental light increased chlorophyll concentration in lettuce (*Lactuca sativa*) and tsukena (*Brassica campestris*). Researchers have found mixed results on the effect of light on height of basil (Beaman et al., 2009; Chang et al., 2008). Beaman et al. (2009) reported sweet basil grown under more light (500 or 600 μmol·m⁻²·s⁻¹) were taller than plants grown under less light (300 or 400 μmol·m⁻²·s⁻¹). Similarly, Chang et al. (2008) found sweet basil height increased by 10.4 cm as DLI increased from 5.2 to 24.9 mol·m⁻²·d⁻¹. Overall, increasing DLI enhanced the growth, branching, and SPAD index of all three basil species, although the effect of DLI on some aspects of morphology, such as height, is less clear and may warrant further study. When the results of Beaman et al. (2009) and Chang et al. (2008) are taken together with our results, we believe basil may be classified as a medium- to high-light crop (Faust, 2011), requiring a DLI of more than 10 mol·m⁻²·d⁻¹ for good- or excellent-quality growth.

Evaluating tissue nutrient concentrations can give us insight on the sufficiency of nutrients supplied to the plant and will help us evaluate plant health. Although there are no published recommended tissue nutrient

concentrations for hydroponically grown basil species or cultivars, Bryson et al. (2014) published recommended sweet basil tissue nutrient concentrations and, although these came from established plants grown outdoors in soil, we believe these recommendations are still valuable for interpreting the results of our study with the three basil species. Sweet basil tissue N concentrations were within the recommended concentration range of 4% to 6%, whereas holy and lemon basil N concentrations slightly exceeded the upper limit under a higher DLI (holy basil) or as DLI was ≥2.0 dS·m⁻¹ (holy and lemon basil). Relative chlorophyll concentration measured by the SPAD meter correlates with N concentration (Bullock and Anderson, 1998; Choi et al., 2011; Gianquinto et al., 2001). Although the SPAD index of holy basil leaves increased with increasing EC, sweet and lemon basil were unaffected (data not shown), further supporting that tissue N was within sufficient ranges. Although P concentrations of basil were between 1.1% and 2.0% and exceeded the recommended range (0.6%–1.0%), no apparent toxicity symptoms were visible. The upper range for tissue K is 2.0%, but our tissue samples had K concentrations ranging from 4.2% to 7.6% across DLIs, ECs, and species. We believe the increased K concentration in the nutrient solution (Table 2) from additions of potassium carbonate to increase pH contributed to the luxury consumption of K. The Mg in holy basil was within or above the recommended range of 0.6% to 1.0%. Although lemon and sweet basil were at or below these values, they appeared healthy and we noted no visual symptoms of Mg deficiency. Although Ca concentrations declined with increasing EC, nearly all Ca concentrations across species and ECs were within the recommended ranges. We postulate that decreasing Mg and Ca concentrations in basil may be a result of the antagonistic relationship between K, Mg, and Ca (Dibb and Thompson, 1985; Johansen et al., 1968). Fageria (1983) reported that Mg and Ca uptake is diminished with increasing K fertilization, which agrees with the results of our study. Although nearly all S and B tissue concentrations were within the recommended ranges, our Cu concentrations were above recommended values. Zinc concentrations in lemon basil were within recommended concentrations, but holy and sweet basil Zn concentrations were above recommendations.

Conclusions

We found no interactions between the nutrient solution EC and DLI on basil growth, morphology, or tissue nutrient concentrations. Basil growth was unaffected and tissue concentrations were generally at or above recommended sufficiency ranges in response to EC, whereas growth was enhanced with increased DLI for all basil species. Nutrient content for basil for plants grown under high DLI was greater than plants grown under a low DLI (data not shown). However, because

the ECs for each solution were maintained at target values consistently throughout the experiment, as is commonly practiced commercially, all nutrient solutions resulted in suitable tissue nutrient concentrations for all basil species under both low and high DLIs. As a result, nutrient solution EC does not need to be adjusted for hydroponic basil production based on DLI alone. Producers are urged to conduct onsite trials to determine optimal nutrient solution concentrations for the cultivars and species they are growing in their greenhouse environment under their production practices.

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