Responses of Six Lamiaceae Landscape Species to Saline Water Irrigation[1]

Shasha Wu[2,3], Youping Sun[3], Genhua Niu[3], Graciela Lizette Grimaldo Pantoja[3,4], and Arturo Castro Rocha[3,4]

Abstract

Salt tolerance of six Lamiaceae ornamental species was evaluated in a greenhouse experiment. Rooted cuttings were transplanted into 3.8 L (1 gal) pots and grown for three weeks in the greenhouse before treatment. Plants were then irrigated six times with a nutrient solution at an electrical conductivity (EC) of 1.2 dS·m^{-1} (control) or a saline solution at EC of 5.0 or 10.0 dS·m^{-1} (EC 5 or EC 10). *Stachys coccinea* (Texas betony) was the most salt tolerant among the six species tested, with less than 50% foliar damage and 56% reduction of dry weight (DW), and less than 10% reductions in gas exchange in EC 10 compared with nontreated plants. *Perovskia atriplicifolia* (Russian sage) and *Lamium maculatum* 'Pink Pewter' (spotted dead nettle) were moderately tolerant with slight salt damage and low mortality rates in EC 10. With visual scores of 3.1 and 3.9 (0 = dead; 5 = excellent), and DW reduction of 36 and 43% in EC 5, Russian sage and spotted dead nettle could grow well when irrigated with low quality water with EC less than 5.0 dS·m^{-1}. *Ajuga reptans* 'Burgundy Glow' (bugleweed), *Poliomintha longiflora* (Mexican oregano), and *Scutellaria suffrutescens* 'Pink Skullcap' (cherry skullcap) were the most sensitive to salinity stress with a survival rate of 80% and 0 in EC 5 and EC 10, respectively.

Index words: groundcover; landscape irrigation; salt tolerance.

Species used in this study: *Ajuga reptans* L. 'Burgundy Glow'; *Lamium maculatum* L. 'Pink Pewter'; *Perovskia atriplicifolia* Benth.; *Poliomintha longiflora* A. Gray; *Scutellaria suffrutescens* S. Watson 'Pink Skullcap'; *Stachys coccinea* Jacq.

Chemicals used in this study: calcium chloride ($CaCl_2$); sodium chloride (NaCl).

Significance to the Horticulture Industry

Due to the rapid increase in urban populations, intense competition for high-quality water among agriculture, industry, and other users is promoting the use of alternative water sources for irrigating landscapes and nursery crops. Alternative water sources, such as municipal reclaimed water and naturally-saline (brackish) water, have relatively high levels of salts, primarily sodium chloride, compared to potable water. Elevated salinity in irrigation water leads to salt damage on plants such as leaf burn, reduced growth, and even death, and impacts the environment and soil negatively if not managed properly. Lamiaceae is a family with thousands of flowering species that are widely used in landscapes and butterfly gardens. Many members of the family are widely cultivated because of their aromatic qualities and ease of cultivation. However, only a small number of species in the Lamiaceae family have been studied for salt tolerance with large variation among species. This study investigated the salt tolerance of six Lamiaceae species by quantifying their growth and physiological responses. Our results indicated that Texas betony was the most salt tolerant, Russian sage and spotted dead nettle were moderately tolerant, while bugleweed, Mexican oregano, and cherry skullcap were the least salt tolerant.

Introduction

The supply of high quality potable water is limited, while demand for it continuously increases due to the increasing United States population (Niu et al. 2007). Using alternative water sources such as municipal reclaimed water to irrigate urban landscapes can help to conserve potable water (Niu et al. 2012). One major concern with alternative water sources for landscape irrigation is the elevated salinity, which may be two to three times higher than potable water and can cause salt damage on salt-sensitive species (Wu et al. 2001). Soil salinization tends to be common in arid and semiarid regions where leaching of salt through the soil profile is poor due to low rainfall. Even though salt tolerance of many commonly used plants has been tested in the past decades (Niu and Rodriguez 2006a,b; Niu et al. 2007; Tanji et al. 2008), considering the large number of plants used in urban landscape, salt tolerance of more ornamental species should be tested as a typical landscape consists of multiple plant species.

Lamiaceae, also known as the mint family, is a family of flowering plants consisting of approximately 7,200 species in 236 genera (Wikimedia Foundation, Inc. 2015). All parts of the plants are frequently aromatic and plants are widely used in butterfly and fragrant gardens. Many members of the family are grown for their aromatic qualities. Salt tolerance of six species in the Lamiaceae family has been studied previously, and salt tolerance was reported to vary largely by species. *Teucrium chamaedrys* L. (wall germander) suffered slight leaf injury from salt exposure (<25%), with 65% shoot dry weight (DW) reduction when irrigated with a salt solution at EC of 12.0 dS·m^{-1} for two months in a greenhouse trial (Niu and Rodriguez 2006a). *Salvia farinacea* Benth. (mealy cup sage) had good quality with minimal foliar damage and 100%

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[2] College of Landscape Architecture, Fujian Agriculture and Forestry University, No. 15 Shangxiadian Rd., Cangshan District, Fuzhou, Fujian 50002, China.

[3] Texas A&M AgriLife Research Center at El Paso, Texas A&M University System, 1380 A&M Circle, El Paso, TX 79927, USA. Corresponding authors Genhua Niu (gniu@ag.tamu.edu) and Youping Sun (youping.sun@ag.tamu.edu).

[4] Departamento de Ciencias Químico-Biológicas, Universidad Autónoma de Cd. Juárez, Chihuahua, Anillo Envolvente y Estocolmo s/n, Cd. Juárez, Chihuahua, CP 32310, México.

survival at EC of 5.5 dS·m^{-1}, and had less than 50% foliar damage and 80% survival at EC of 7.3 dS·m^{-1} after grown for 5 weeks in a 25% light exclusion shade house, indicating its moderate salt tolerance (Niu et al. 2012). *Rosmarinus officinalis* L. 'Huntington Carpet' had no foliar damage from salt exposure at an EC of 5.4 dS·m^{-1} treatment in raised beds under field conditions from June to September (Niu et al. 2007). *Salvia coccinea* P.J. Buchoz ex Etlinger (Texas sage) grew well at an EC of 4.0 dS·m^{-1}, whereas *Agastache cana* (Hook.) Woot. & Standl. (mosquito plant) exhibited moderate foliar damage in the same salinity treatment (Niu and Rodriguez 2006b). *Monarda citriodora* Cerv. Ex Lag. (lemon horsemint) was sensitive to salinity stress since it did not survive at an EC of 2.8 dS·m^{-1} (Niu et al. 2012).

The information on the salt tolerance of species and cultivars belonging to the Lamiaceae family is very limited considering the large number of ornamental plants in this family that are used in the landscapes. Therefore, the response of more species and cultivars to salinity stress should be evaluated to provide more choices for landscapes irrigated with poor-quality water. Four groundcover plants, *Ajuga reptans* L. 'Burgundy Glow' (bugleweed), *Lamium maculatum* L. 'Pink Pewter' (spotted dead nettle), *Scutellaria suffrutescens* 'Pink Skullcap' (cherry skullcap), and *Stachys coccinea* Jacq. (Texas betony), and two border plants, *Perovskia atriplicifolia* Benth. (Russian sage) and *Poliomintha longiflora* A. Gray (Mexican oregano), were selected for this study. Russian sage was the only woody plant tested as all others are herbaceous perennials. Cherry skullcap, spotted dead nettle, and Texas betony are attractive groundcovers in the garden. All plants are reported to attract bees, butterflies, and/or birds, except spotted dead nettle and cherry skullcap (Lady Bird Johnson Wildflower Center 2015). Mexican oregano, cherry skullcap, and Texas betony are xeriscape plants, but the salt tolerance of these species is unknown. Therefore, the objective of this study was to examine the growth and physiological (gas exchange, leaf greenness, chlorophyll fluorescence, and mineral accumulation) responses of these six ornamental plant species of Lamiaceae family to a range of salinity levels.

Materials and Methods

Plant growing conditions. Rooted cuttings of six perennials in the Lamiaceae family in 70- or 125-cell plug trays were received from Southwest Perennials (Dallas, TX) on January 9, 2015, and were transplanted into 3.8-L (1 gal) pots with Metro-Mix 360 (SunGro Hort., Bellevue, WA) on January 12 with one plant per pot. Three weeks after transplanting, saline water irrigation treatments were initiated. Before treatment, all the plants were well irrigated with a nutrient solution containing 1 g·L^{-1} (150 ppm N) 15N-2.2P-12.5K (Peters 15-5-15 Ca-Mg Special; Scotts, Marysville, OH) to reverse osmosis water. The average air temperature in the greenhouse was 26.9/23.5 C (80/74 F) (day/night), the average daily light integral was 13.3 mol·m^{-2}·d^{-1}, and the average relative humidity was 29.5% during the experiment period.

Saline solution treatments. Saline solutions at an EC of 5.0 dS·m^{-1} (EC 5) were created by adding 1.20 g·L^{-1} (1,200 ppm) sodium chloride (NaCl) and 1.16 g·L^{-1} (1,160 ppm) calcium chloride ($CaCl_2$) to the nutrient solution mentioned above, while saline solutions at an EC of 10.0 dS·m^{-1} (EC 10) were made by adding 2.80 g·L^{-1} (2,800 ppm) NaCl and 2.67 g·L^{-1} (2,670 ppm) $CaCl_2$ to the nutrient solution. Saline solutions were prepared in 114-L (30 gal) tanks and EC of the two salinity levels were confirmed using an EC meter (Model B173; Horiba, Ltd., Kyoto, Japan) before irrigation. The average EC in nutrient solution (control), EC 5, and EC 10 treatments were 1.2 ± 0.1, 5.1 ± 0.2, and 10.3 ± 0.3 dS·m^{-1}, respectively. Plants were irrigated with treatment solutions weekly from February 3 to March 10, six times in total. Between the two treatment solution irrigations, nutrient solution was applied when necessary. Irrigation frequency varied with environmental condition and treatment and the necessity of irrigation was determined by checking the dryness of the substrate. For example, water use of plants at the higher salinity was less and irrigated less often compared to the plants in the control. Plants were irrigated manually with 1 L (34 fl oz) treatment solution per pot, resulting in a leaching fraction of approximately 22% to prevent rapid salt accumulation. Plants were harvested from March 23 to March 26. Each treatment contained ten plants per species.

Survival percentage, leachate EC, and substrate EC. Before harvest, live plants were counted in each treatment and survival percentage was calculated. The leachate ECs for all treatments were determined using a pour-through method (Cavins et al. 2008) for three plants per treatment per species after each saline solution treatment. The substrate final ECs were determined using a saturated paste extract (Gavlak et al. 1994) for three pots per treatment per species.

Foliar damage from salinity. At the end of the experiment, foliar damage by salts, including leaf edge burn, necrosis, and discoloration of each plant, was rated visually by giving a score based on a criterion reference scale from 0 to 5, where 0 = dead; 1 = over 90% foliar damage; 2 = moderate (50 to 90%) foliar damage; 3 = slight (less than 50%) foliar damage; 4 = good quality with minimal foliar damage; and 5 = excellent with no foliar damage. The foliar damage rating did not consider the plant size or flower count/size.

Growth parameters. Plant height (cm), from the pot rim to the top of the shoot (usually to the tallest flower), and crown diameter (cm) at perpendicular directions was recorded at the end of the experiment. The average of height and crown diameters was calculated as a growth index (Niu et al. 2007). Leaf area (cm^2) of all live plants was determined using a LI-3100C area meter (LI-COR® Biosciences, Lincoln, NE). Since all the species have compound inflorescences, number of inflorescences for each live plant was counted. Number of shoots and total shoot length of each live plant were measured. On termination, above-ground parts (including stems, leaves and flowers) were harvested and DW was determined after oven-drying at 70 C (158 F) for four days.

Gas exchange. Stomatal conductance (g_s), transpiration (E), and leaf net photosynthesis (P_n) of seven plants per species per treatment were measured at the end of the experiment using a CIRAS-2 portable photosynthesis system (PP Systems, Amesbury, MA) with an automatic universal PLC6 broad leaf cuvette. The 3rd fully expanded leaf, counting from the top of the plant downward, was labeled for the measurements. The environmental conditions within the cuvette were maintained at leaf temperature of 25 C (77 F), photosynthetic photon flux (PPF) of 1,000 μmol·m^{-2}·s^{-1} (5,000 foot-candle), and CO$_2$ concentration of 375 μmol·mol^{-1} (375 ppm). Data were recorded when the environmental conditions and gas exchange parameters in the cuvette stabilized. These measurements were taken on sunny days between 10 am and 2 pm, and plants were well watered to avoid water stress.

Leaf greenness and chlorophyll fluorescence. Leaf greenness (or relative chlorophyll content) was measured as the optical density or SPAD reading using a handheld chlorophyll meter (Minolta Camera Co., Osaka, Japan) at the end of the experiment on November 3. The healthy leaves in the middle of the shoot were chosen for measurement. Leaf chlorophyll fluorescence was also estimated in the morning on young mature leaves using a Plant Efficiency Analyzer (Handy PEA, Hansatech Instruments Ltd., Kings Lynn, UK) on March 19 and 20. Four plants per species per treatment were selected randomly for measurement. Minimal florescence (F_0), maximum fluorescence (F_m), the maximal photochemical efficiency of PSII (F_v / F_m, $F_v = F_m - F_0$), and performance index (P_i) were measured to examine the effect of elevated salinity on leaf photosynthesis.

Mineral analysis. To analyze shoot and leaf Na, Cl, K, and Ca concentrations, a shoot from each of four of the ten plants per treatment per species were randomly selected. When there was no live plants in EC 10, the dead ones were used. Dried tissue was ground to pass a 40-mesh screen with a stainless Wiley mill (Thomas Scientific, Swedesboro, NJ). Plant powder samples were extracted with 2% acetic acid (EM Science, Gibbstown, NJ) for determining chloride using the method described in Gavlak et al. (1994). The concentration of chloride was determined by a M926 Chloride Analyzer (Cole Parmer Instrument Company, Vernon Hills, IL). Plant powder samples were submitted to the Soil, Water and Forage Testing Laboratory at Texas A&M University (College Station, TX) for determining alkaline earth metals (Na, Ca, K). In brief, plant powder samples were digested in nitric acid following the protocol described by Havlin and Soltanpour (1989). Na, Ca, and K in digested samples were analyzed by SPECTROBLUE Inductively Coupled Plasma-Optical Emission Spectrometry (SPECTRO Analytical Instruments Inc., Mahwah, NJ) and reported on a dry plant basis as described by Isaac and Johnson (1975).

Experimental design and statistical analysis. The experiment utilized a split-plot design with the salinity treatment as the main plot and six species as the subplot with ten replications per treatment for each species. Due to different plant growth habits, a one-way analysis of variance (ANOVA) was performed separately for each species for all data. Means separation among treatments was conducted using Tukey's honest significant difference (HSD) multiple comparison at $P < 0.05$. When the plants in EC 10 treatment were all dead, the parameter of control and EC 5 were analyzed by Student's t test at $P < 0.05$. All statistical analyses were performed using JMP (Version 12, SAS Institute Inc., Cary, NC).

Results and Discussion

Leachate EC, survival percentage, and visual quality. Leachate EC in control plants ranged from 2.4 to 3.4 dS·m^{-1} during the entire period of the experiment (Fig. 1). The leachate EC in EC 5- and EC 10-treated plants increased from 5.1 to 10.2 dS·m^{-1} and from 9.8 to 18.1 dS·m^{-1}, respectively. From March 3 to March 17, all the plants were watered with nutrient solution, which resulted in the decrease of leachate EC in both EC 5 and EC 10 treatments. The final substrate ECs of control, EC 5-, and EC 10-treated plants were 1.7 ± 0.2, 2.9 ± 0.3, and 5.0 ± 0.6 dS·m^{-1}, respectively (data not shown). The substrate EC increased as the salinity of irrigation water increased, indicating that salts accumulated in the root zone.

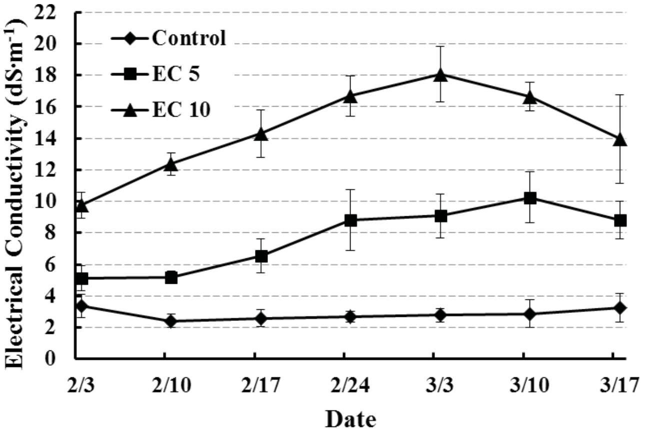

Fig. 1. Variation of weekly leachate electrical conductivity (EC) during the experimental period from container-grown plants. The control represents plants treated with EC at 1.2 dS·m^{-1} (nutrient solution); EC 5 represents plants treated with EC at 5.0 dS·m^{-1}; and EC 10 represents plants treated with EC at 10.0 dS·m^{-1}. All plants were watered with nutrient solution after the 6th treatment on March 10 until harvest on March 23. Data were pooled across all six Lamiaceae species as species did not affect leachate EC. Vertical bars represent standard errors.

Salinity treatment decreased the survival and aesthetic values of all the species except Texas betony (Table 1). All plants of Texas betony were alive at the end of the experiment with minimal foliar damage in the EC 5 and EC 10 treatments. Compared with the control, EC 5 reduced the survival percent of Mexican oregano and cherry skullcap by 30 and 20%, respectively, and caused moderate (50 to 90%) foliar damage in both species. The remaining four species all

Table 1. Survival rate and visual score of six Lamiaceae species irrigated with nutrient solution [Electrical conductivity (EC) = 1.2 dS·m^{-1}; control] or saline solution [EC = 5.0 dS·m^{-1} (EC 5) or 10.0 dS·m^{-1} (EC 10)]^z.

	Survival rate (%)			Visual score^y		
Species	Control	EC 5	EC 10	Control	EC 5	EC 10
Bugleweed	100	100	0	4.9a	4.3b	0.0c
Cherry skullcap	100	80	0	5.0a	1.7b	0.0c
Mexican oregano	100	70	0	5.0a	2.0b	0.0c
Russian sage	100	100	90	5.0a	3.9b	2.7c
Spotted dead nettle	100	100	70	4.8a	3.1b	2.1c
Texas betony	100	100	100	5.0a	4.0b	3.7b

^{z}Means with same letters within a row are not significantly different among treatments by Tukey's honest significant difference (HSD) test at $P < 0.05$.

^{y}Visual score: 0 = dead; 1 = over 90% foliar damage; 2 = moderate (50 to 90%) foliar damage; 3 = slight (less than 50%) foliar damage; 4 = good quality with minimal foliar damage; and 5 = excellent with no foliar damage.

Table 2. **Growth index, leaf area, and number of inflorescences of six Lamiaceae species irrigated with nutrient solution [Electrical conductivity (EC) = 1.2 dS·m^{-1}; control] or saline solution [EC = 5.0 dS·m^{-1} (EC 5) or 10.0 dS·m^{-1} (EC 10)][z].**

	Growth index (cm)			Leaf area (cm^2)			Number of inflorescences		
Species	**Control**	**EC 5**	**EC 10**	**Control**	**EC 5**	**EC 10**	**Control**	**EC 5**	**EC 10**
Bugleweed	20.5a	14.4b	—[y]	1218.9a	395.9b	—	1a	0b	—
Cherry skullcap	21.2a	13.5b	—	273.2a	42.0b	—	23a	4b	—
Mexican oregano	35.3a	28.6b	—	403.9a	123.2b	—	0a	0a	—
Russian sage	56.7a	57.4a	37.6b	470.9a	437.3a	154.6b	3a	3a	3a
Spotted dead nettle	32.7a	26.1b	21.1c	2844.6a	1119.6b	682.0b	55a	28b	7c
Texas betony	67.8a	61.5a	44.0b	1949.3a	1731.2b	1110.3c	33a	24b	9c

[z] Means followed by same lowercase letters within a row are not significantly different between treatments by Student's *t* test or among treatments by Tukey's honest significant difference (HSD) multiple comparison at $P < 0.05$.

[y] Data were not collected due to plant death.

survived and had 3.1 to 4.3 visual scores in EC 5. Bugleweed, Mexican oregano, and cherry skullcap in EC 10 began to die on March 1 (27 days after the first treatment) and all plants died by the end of the experiment. The mortality rates of spotted dead nettle and Russian sage were 30 and 10% in EC 10, respectively. The visual scores of spotted dead nettle and Russian sage in EC 10 were 2.1 and 2.7, respectively, indicating moderate foliar damage from the salts.

For each salinity level, it was possible to select a number of landscape plants whose aesthetic values are not or are only slightly affected (Bernstein et al. 1972). Obviously, as the salinity of irrigation water increased, the number of plants that can tolerate the salt stress becomes smaller (Niu and Cabrera 2010). Furthermore, each crop has a threshold level of tolerance to salinity, which differs among species and even among cultivars (Maas 1986). For ornamental plants, maximizing yield or biomass is not the target. Instead, maintaining aesthetic appearance is more important, and survival rate and injury can be assessed visually (Niu and Rodriguez 2006a; Niu and Cabrera 2010). According to these criteria, bugleweed, Mexican oregano, and cherry skullcap were less tolerant to the salts tested compared to the other three species tested in this research.

Plant growth. All growth data including growth index, leaf area, number of inflorescence, number of shoots, total shoot length, and DW decreased significantly as the salinity levels increased (Tables 2 and 3). There was no obvious change in the growth index of Russian sage and Texas betony between the control and EC 5-treated plants. Compared with control plants, 19, 20, 30, and 36% reduction of growth index were found in Mexican oregano, spotted dead nettle, bugleweed, and cherry skullcap, respectively, treated in EC 5. EC 10 application reduced the growth index of the three surviving species (Russian sage, Texas betony, and spotted dead nettle) by 34, 35, and 35%, respectively.

The leaf area of Russian sage was not reduced by EC 5, compared with the control plants. EC 5 application significantly reduced the leaf area of the other five species with Texas betony having the least (11%) and cherry skullcap having the greatest reduction (85%), and the reduction of the other three species ranged from 61 to 70%. The reductions of leaf area in Russian sage, Texas betony, and spotted dead nettle in EC 10 were 36, 43, and 76%, respectively.

Number of inflorescences was significantly reduced by salinity in cherry skullcap, spotted dead nettle, and Texas betony, with reductions of 83, 50, and 26%, respectively, in EC 5, and 86 and 74%, respectively, for the latter two species in EC 10. Cherry skullcap, spotted dead nettle, and Texas betony in the control treatment had relatively more inflorescences, 23, 55, and 33 per plant, respectively, compared to plants in the salinity treatments. For bugleweed, short spikes of blue flowers stand upright above the low, spreading foliage from mid to late spring. The plants for this species in the current experiment just began to bloom at the end of the experiment, thus any effect of salinity on its flower inflorescence could not be observed. However, considering the reduced growth index, leaf area, and 100% mortality in EC 10, the number of inflorescence would likely be reduced by the increased EC of the EC 10 treatment. There was no difference in the inflorescence numbers of Russian sage, having 3 inflorescences per plant in all treatments. For Mexican

Table 3. **Number of shoots, total shoot length, and dry weight of six Lamiaceae species irrigated with nutrient solution [Electrical conductivity (EC) = 1.2 dS·m^{-1}; Control] or saline solution [EC = 5.0 dS·m^{-1} (EC 5) or 10.0 dS·m^{-1} (EC 10)] in the greenhouse[z].**

	Number of shoots			Total shoot length (cm)			Dry weight (g)		
Species	**Control**	**EC 5**	**EC 10**	**Control**	**EC 5**	**EC 10**	**Control**	**EC 5**	**EC 10**
Bugleweed	26a	14b	—[y]	84.7a	46.8b	—	8.9a	4.1b	—
Cherry skullcap	87a	10b	—	839.9a	81.1b	—	6.4a	1.9b	—
Mexican oregano	29a	11b	—	408.0a	140.3b	—	7.3a	2.8b	—
Russian sage	4a	4a	3a	270.3a	205.1ab	131.8b	15.7a	10.1b	3.4c
Spotted dead nettle	69a	41b	17c	985.9a	453.8b	177.8c	24.1a	13.9b	7.6c
Texas betony	56a	44b	17c	1424.8a	1030.1b	376.2c	31.7a	28.5b	13.9c

[z] Means followed by same lowercase letters within a row are not significantly different between treatments by Student's *t* test or among treatments by Tukey's honest significant difference (HSD) multiple comparison at $P < 0.05$..

[y] Data were not collected due to plant death.

oregano, it flowers in midsummer; all the plants of this species in the current experiment did not flower.

Shoot growth parameters. The number of shoots, total shoot length, and shoot DW for all six species decreased with the increasing salinity, except the number of shoots in Russian sage (Table 3). There were 3 to 4 shoots per plant for Russian sage in the control, EC 5, and EC 10 treatments. Its total shoot length was not affected by EC 5, but was severely reduced in EC 10 by 51% compared with control plants. Shoot DW of Russian sage was reduced by 36% in EC 5 and 79% in EC 10. Shoot DW of Texas betony and spotted dead nettle was reduced by 10 and 42% in EC 5, and 56 and 69% in EC 10, compared to their respective control. For bugleweed, cherry skullcap, and Mexican oregano, all plants died in EC 10 and had reduced shoot number, total shoot length, and shoot DW in EC 5 compared to control plants. The maximum reductions of the three shoot parameters were found in cherry skullcap, which had reductions of 89% in shoot number, 90% in total shoot length, and 70% in shoot DW in EC 5, compared to control plants, with lower reductions seen in Mexican oregano and bugleweed.

Salinity can impair plant function, growth, and developmental processes. Plants subjected to salt stress undergo low osmotic stress and ion toxicity (Taiz and Zeiger 2015). Salt-tolerant plants usually have less growth reduction and less foliar injury at elevated salinity (Cassaniti et al. 2009, Niu and Rodriguez 2006a). Based on these criteria, Texas betony was more salt tolerance than the other five species, whereas bugleweed, cherry skullcap, and Mexican oregano were more sensitive to salinity.

Gas exchange and leaf greenness (SPAD reading). Gas exchange rates of cherry skullcap were not measured due to the small leaves. Salinity had a different impact on the g_s, E, and P_n of the five species tested, with Texas betony as an exception (Table 4). There was no difference between control and EC 5-treated plants in g_s, E, and P_n of Russian sage and Mexican oregano, but EC 10 significantly reduced g_s, E, and P_n by 34, 23, and 27%, respectively. EC 5 application decreased bugleweed and spotted dead nettle g_s by 32 and 47%, E by 20 and 26%, and P_n by 19 and 30%, respectively, while EC 10 further reduced spotted dead nettle by 48% in g_s, 36% in E, and 34% in P_n. The reductions of the gas exchange rates of the five species were in coincident with the negatively impact of salinity on growth parameters mentioned above.

Salinity did not affect the SPAD reading of Russian sage. EC 5 application decreased the SPAD reading of Mexican oregano and cherry skullcap by 18 and 26%, respectively. SPAD readings of spotted dead nettle and Texas betony were not impacted by EC 5, but were by EC 10. Leaf discoloration is one of the typical initial foliage damage symptoms from excess salt exposure (Devitt et al. 2005), which may be reflected by the decreased SPAD readings. Therefore, SPAD readings may be a tool to rapidly quantify the initial or mild salt damage (Niu et al. 2007). Reduction in chlorophyll concentration in leaves might be due to a loss of photosynthetic capacity and the inhibitory effect of accumulated ions on biosynthesis of the chlorophyll fraction (Hakim et al. 2014). NaCl-induced decrease in chlorophyll level has widely been reported in glycophytes and halophytes (Abdullah et al. 2001).

Salinity of irrigation water did not influence F_v / F_m and P_i of the five species measured (data not shown), indicating that the efficacy of photosystem II (PSII) was not impacted by the salinity stress (Maxwell and Johnson 2000). Naumann et al. (2009) reported that chlorophyll fluorescence did respond to salinity and there was a positive relationship between physiological reflectance index and $\Delta F/F'_m$ for *Myrica cerifera* L. (southern wax myrtle) ($r^2 = 0.79$) and *Iva frutescens* L. (Jesuit's bark) ($r^2 = 0.72$).

Mineral concentration. Salinity had a significant effect on leaf Na and Cl of the six species (Table 5). Leaf Na concentration of Texas betony in EC 10 was the highest (56.8 $mg \cdot g^{-1}$ DW) among the tested species, and only Texas betony plants survived in EC 10. These results indicate that Texas betony can tolerate high Na accumulation in the tissue. Leaf Na of spotted dead nettle and Russian sage did not change in EC 5, but increased approximately 12 and 27 times in EC 10 compared to control plants. Leaf Cl concentration of these two species in EC 10 increased by approximately 12 times compared to their respective control, which was the least among all tested species. Compared with the control, EC 5 did not affect the leaf Na concentration of cherry skullcap but it increased the leaf Cl concentration by 17 times. Leaf Na content of cherry skullcap plants in EC 10 was the least (2.5 $mg \cdot g^{-1}$ DW) among the tested species, while their Cl concentration was the highest (194.3 $mg \cdot g^{-1}$ DW), which

Table 4. Stomatal conductance (g_s), transpiration (E), leaf net photosynthesis (P_n), and SPAD of six Lamiaceae species irrigated with nutrient solution [Electrical conductivity (EC) = 1.2 $dS \cdot m^{-1}$; Control] or saline solution [EC = 5.0 $dS \cdot m^{-1}$ (EC 5) or 10.0 $dS \cdot m^{-1}$ (EC 10)] in the greenhouse. Cherry skullcap was not measured for gas exchange due to its small leaves[z].

	g_s ($mmol \cdot m^{-2} \cdot s^{-1}$)			E ($mmol \cdot m^{-2} \cdot s^{-1}$)			P_n ($\mu mol \cdot m^{-2} \cdot s^{-1}$)			SPAD		
Species	Control	EC 5	EC 10	Control	EC 5	EC 10	Control	EC 5	EC 10	Control	EC 5	EC 10
Bugleweed	716.7a	486.1b	—[y]	6.9a	5.8b	—	12.9a	10.5b	—	37.6a	37.2a	—
Cherry skullcap	—	—	—	—	—	—	—	—	—	40.1a	29.6b	—
Mexican oregano	217.9a	148.7a	—	3.5a	2.8a	—	12.4a	8.4a	—	51.2a	42.2b	—
Russian sage	760.3a	1069.6a	501.3b	7.0ab	8.0a	5.4b	22.9ab	24.6a	16.8b	41.2a	49.8a	40.6a
Spotted dead nettle	414.4a	220.3b	214.1b	5.1a	3.8b	3.3ab	11.3a	8.0b	7.5b	30.2a	29.2ab	25.9b
Texas betony	379.9a	356.3a	362.7a	5.2a	5.1a	4.8a	17.1a	16.8a	15.8a	45.3a	47.0ab	44.1b

[z] Means followed by same lowercase letters within a row are not significantly different between treatments by Student's *t* test or among treatments by Tukey's honest significant difference (HSD) multiple comparison at $P < 0.05$.

[y] Data were not collected due to plant death.

Table 5. Leaf ion concentration of six Lamiaceae species irrigated with nutrient solution [Electrical conductivity (EC) = 1.2 $dS\cdot m^{-1}$; Control] or saline solution [EC = 5.0 $dS\cdot m^{-1}$ (EC 5) or 10.0 $dS\cdot m^{-1}$ (EC 10)] in the greenhouse[z].

		Ion concentration ($mg\cdot g^{-1}$)			
Species	**Treatment**	**Na**	**Cl**	**K**	**Ca**
Bugleweed	Control	4.2c	3.7c	46.0a	9.7c
	EC 5	25.7b	51.3b	20.3b	15.9b
	EC 10	48.5a	144.0a	16.1b	38.1a
Cherry skullcap	Control	0.2b	4.4c	40.8a	7.6c
	EC 5	1.0b	80.8b	41.0a	12.5b
	EC 10	2.5a	194.3a	36.7a	19.2a
Mexican oregano	Control	0.2c	3.9c	30.6a	10.1c
	EC 5	6.2b	31.4b	27.1a	18.4b
	EC 10	37.7a	129.3a	26.9a	36.1a
Russian sage	Control	0.5b	2.4b	37.4a	7.8b
	EC 5	4.0b	10.0b	32.7a	7.5b
	EC 10	13.0a	29.4a	22.3b	12.1a
Spotted dead nettle	Control	0.7b	5.7c	59.5a	13.4b
	EC 5	2.9b	31.2b	58.5a	18.2ab
	EC 10	8.9a	68.9a	57.1a	26.3a
Texas betony	Control	0.3c	2.5c	22.6a	9.3c
	EC 5	17.9b	33.3b	21.4ab	25.6b
	EC 10	56.8a	54.7a	19.2b	48.4a

[z] For each species, means followed by same letters within a column are not significantly different between treatments by Tukey's honest significant difference (HSD) multiple comparison at $P < 0.05$.

was 43 times higher than that of their control. Bugleweed and Mexican oregano had the second and third highest leaf Na and Cl concentrations in EC 10, which were 48.5 and 37.7 $mg\cdot g^{-1}$ DW (Na), and 144.0 and 129.3 $mg\cdot g^{-1}$ DW (Cl). It should be noted that leaf Na content of bugleweed in control was much higher than that of the others.

Elevated salinity did not change the concentration of K in spotted dead nettle, Mexican oregano, and cherry skullcap. Leaf K concentration of bugleweed, Russian sage, and Texas betony in EC 10 were 64.9, 40.4, and 15% times less than their respective counterparts in the control.

As the salinity levels increased, leaf Ca concentration in all species increased significantly with the exception of spotted dead nettle and Russian sage (Table 5). The Ca concentrations in bugleweed, Mexican oregano, and Texas betony in EC 10 were 2.9, 2.6, and 4.2 times higher than their respective controls.

Among the six species investigated, Texas betony had the highest leaf Na and Ca concentration, while the lowest Cl concentration in EC 10, indicating that the mechanism of salt tolerance in Texas betony is through the tolerance of high Na in plant tissue (Munns and Tester 2008). For bugleweed, Mexican oregano, and cherry skullcap, higher Cl concentrations were found in the dead leaf tissue of plants in EC 10, which led to severe foliar injury and death of the plants.

Texas betony was the most salt-tolerant species among the six investigated Lamiaceae ornamental species, with the least foliar damage, the least reduction of DW, no reduction in gas exchange rates compared with control plants, and the highest leaf Na concentration, indicating that this species has high adaptation ability to the high shoot Na concentration. Russian sage and spotted dead nettle were moderately salt tolerant with slight foliar damage and low mortality rates in EC 10. Bugleweed, cherry skullcap, and Mexican oregano were sensitive to salinity stress with no survival in EC 10.

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