

Growth, Gas Exchange, and Mineral Nutrients of Ornamental Grasses Irrigated with Saline Water

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Abstract. Ornamental grasses are commonly used in urban landscapes in Utah and the Intermountain West of the United States. The relative salt tolerance of *Eragrostis spectabilis* (Pursh) Steud. (purple love grass), *Miscanthus sinensis* Andersson ‘Gracillimus’ (maiden grass), *Panicum virgatum* L. ‘Northwind’ (switchgrass), and *Schizachyrium scoparium* (Michx.) Nash (little bluestem) were evaluated in a greenhouse. Plants were irrigated with a nutrient solution at an electrical conductivity (EC) of 1.2 dS·m⁻¹ (control), or saline solution at an EC of 5.0 or 10.0 dS·m⁻¹. At harvest (65 days after the initiation of treatment), *P. virgatum* and *S. scoparium* exhibited no foliar salt damage, and *E. spectabilis* and *M. sinensis* had minimal foliar salt damage when irrigated with saline solution at an EC of 5.0 dS·m⁻¹. At an EC of 10.0 dS·m⁻¹, *P. virgatum* and *S. scoparium* still had no foliar salt damage, but *E. spectabilis* and *M. sinensis* displayed slight foliar salt damage, with visual scores greater than 3 (0 = dead; 5 = excellent). Compared with the control, saline solution at an EC of 5.0 and 10.0 dS·m⁻¹ reduced the shoot dry weight of all ornamental grasses by 25% and 46%, respectively. The leaf sodium (Na⁺) concentration of *E. spectabilis*, *M. sinensis*, *P. virgatum*, and *S. scoparium* irrigated with saline solution at an EC of 10.0 dS·m⁻¹ increased 14.3, 52.6, 5.3, and 1.7 times, respectively, and the chloride (Cl⁻) concentration increased by 9.4, 11.1, 2.8, and 2.7 times, respectively. As a result of the salt-induced water deficit, plant height, leaf area, number of inflorescences and tillers, net photosynthesis rate (P_n), stomatal conductance (g_s), and transpiration rate of four tested ornamental grasses decreased to some extent. Although high Na⁺ and Cl⁻ accumulated in the leaf tissue, all ornamental grass species still had a good visual quality, with average visual scores greater than 3. In conclusion, all ornamental grasses showed a very strong tolerance to the salinity levels used in this research.

Water conservation is becoming critically important throughout the United States, especially in Utah and the Intermountain West, one of the driest and fastest growing regions in the United States. The green industry in this arid to semiarid region would earnestly consider alternative water sources such as treated and reclaimed sewage effluent (reclaimed water) for water conservation and improved environmental stewardship. Reclaimed water has been a viable alternative source for landscape irrigation in Utah, with an established use record on golf courses. Reclaimed water is also used by a handful of large corporate and municipal parks and

landscapes in arid and semiarid urban areas across the Desert Southwest (Grieve, 2011; Tanji et al., 2008). As Utah and the West work toward improved water conservation, the chances are good that water will be restricted until only minimums are applied. This has the potential to reduce the leaching fraction of irrigation to the point that soil salinity will gradually increase, especially in salt-prone areas using reclaimed water. It is essential to select salt-tolerant plants for landscape use in those salt-prone areas.

Reclaimed water has a relatively high salinity level and undesirable specific ions (Grieve, 2011) that could impose salt stress

on a large number of landscape plants (Niu and Cabrera, 2010; Sun et al., 2015a; Wu and Dodge, 2005). Landscape plants have been evaluated for salt tolerance. Since 2005, researchers at the Texas A&M AgriLife Research Center at El Paso have screened more than 150 landscape plant species and/or cultivars in greenhouse conditions (Niu and Cabrera, 2010; Niu et al., 2011; Sun et al., 2015a). All these studies showed consistently that the salt tolerance of landscape plants varies highly with species and/or cultivars (Chen et al., 2017; Liu et al., 2017; Sun et al., 2015a). However, limited research-based information on the salt tolerance of ornamental grasses is available.

Ornamental grasses have drawn considerable attention in the U.S. green industry as a result of their high drought tolerance, low maintenance input, and the unique textures and patterns they contribute to the landscape (Gunnell et al., 2015). Nursery production and landscape use have expanded significantly, with an estimated \$158 million worth of ornamental grasses sold annually in the United States (U.S. Department of Agriculture, 2015). Ornamental grasses are popular in urban landscapes in Utah and the Intermountain West of the United States. *Eragrostis spectabilis* (purple love grass) is a warm-season bunchgrass with flat, coarse green leaves and soft reddish purple flowers in a loose and open inflorescence (Missouri Botanical Garden, 2018). The inflorescence of purple love grass is good for dried flower arrangements. *Miscanthus sinensis* ‘Gracillimus’, commonly called chinese silver grass or maiden grass, is a clump-forming warm-season grass that features narrow green leaves with a silver midrib and tiny reddish copper flowers in tassel-like inflorescences (Missouri Botanical Garden, 2018). Maiden grass produces long-lasting dried flowers for winter interest. *Panicum virgatum* ‘Northwind’ (switchgrass), an introduction of Northwind Perennial Farm (Burlington, WI), is a warm-season grass with finely textured, pink-tinged, branched panicle inflorescences and olive- to bluish green foliage forming a compact, narrow, erect clump (Missouri Botanical Garden, 2018). *Schizachyrium scoparium* (little bluestem) is one of the dominant grasses of the tallgrass prairie region and features upright clumps of slender, flat, linear green leaves with purplish bronze flowers in racemes (Missouri Botanical Garden, 2018). These four ornamental grass species belong to the grass family (Poaceae). They tolerate a wide range of soils and drought conditions and are accent specimens for garden and urban landscapes.

The salt tolerance of a few ornamental grasses have been evaluated. In general, cool-season grasses usually have less salt tolerance than warm-season grasses (Schiavon et al., 2012, 2014). In a 4-month experiment, *Leymus arenarius* (L.) Hochst. (sand ryegrass), *Muhlenbergia capillaris* (Lam.) Trin. (pink muhly grass), and *Pennisetum alopecuroides* (L.) Spreng. (fountain grass) showed a very strong salt tolerance with an

acceptable visual quality, although plant growth was inhibited by the increasing salinity (Sun and Palmer, 2018). *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths (blue grama) has moderate tolerance to salinity when grown at a saturated soil extract (EC_e) of 4 to 8 $dS\cdot m^{-1}$ (Kratsch et al., 2008), and its salt tolerance varies within ecotypes and is greater at the germination stage than the mature stage (Zhang et al., 2012). *P. alopecuroides* 'Hameln' is slightly more tolerant to salt spray than *M. sinensis* 'Gracillimus' (Alvarez, 2006). *Pennisetum clandestinum* Hochst. ex Chiov. (kikuyugrass) is a suitable candidate for the saline-sodic water reuse system with a threshold EC_e of 8.0 $dS\cdot m^{-1}$ (Grieve et al., 2004, 2012). Pink muhly grass can survive at sodium chloride (NaCl) irrigation rates of 10,000 $mg\cdot L^{-1}$ (corresponding to an EC of $\approx 12.5\ dS\cdot m^{-1}$), which is up to 20 times greater than graywater (Christova-Boal et al., 1996; LeCompte et al., 2016). Because diverse ornamental grasses are produced by the green industry, further research is needed to identify salt-tolerant ornamental grasses for landscape use. This study was designed to assess the salt tolerance of four commonly used ornamental grasses in response to saline

solution irrigation through comparing their growth, gas exchange, and mineral nutrients.

Materials and Methods

Plant materials, treatments, and growing conditions. Ornamental grasses including *E. spectabilis*, *M. sinensis* 'Gracillimus', *P. virgatum* 'Northwind', and *S. scoparium* were used in this study. On 5 Oct. 2017, plugs (≈ 10 cm tall) in 32-cell trays ($5.5 \times 5.5 \times 10.5$ cm) were received from Hoffman Nursery (Rougemont, NC). They were transplanted in 3.8-L, injection-molded, polypropylene pots (PC1D-4; Nursery Supplies, Orange, CA) containing a soilless growing substrate [75% peatmoss (Canadian sphagnum peatmoss; SunGro Horticulture, Agawam, MA), 25% vermiculite (Therm-O-Rock West, Chandler, AZ), and 0.8 $kg\cdot m^{-3}$ white athletic field-marking gypsum (92% calcium sulfate dihydrate, 21% calcium, 17% sulfur; Western Mining and Minerals, Bakersfield, CA)]. All plants were irrigated with tap water (Table 1) as needed. Plants were kept in a greenhouse in Logan, UT (lat. $41^{\circ}45'28''N$, long. $111^{\circ}48'47''W$; elevation, 1409 m) before the experiment.

On 13 Apr. 2018, all plants were pruned to 15 cm high and repotted into 7.6-L, injection-molded, polypropylene containers (No. 2B, Nursery Supplies) with the same potting media described earlier. On 25 Apr., uniform plants were chosen for the experiment, and all plants were pruned again to 15 cm high. From 25 Apr. to 25 June, plants were irrigated roughly every 4 d with a nutrient solution at an EC of 1.2 $dS\cdot m^{-1}$, or saline solution at an EC of 5.0 or 10.0 $dS\cdot m^{-1}$ (Table 1) at 1.5 L per pot, resulting in a leaching fraction of $34.5\% \pm 15.4\%$. A nutrient solution was prepared by adding 0.8 $g\cdot L^{-1}$ 15N–2.2P–12.5K water-soluble fertilizer (Peters Excel 15–5–15 Ca-Mag Special; ICL Specialty Fertilizers, Dublin, OH) to the tap water and used as the control. The saline solution was created by adding NaCl and calcium chloride ($CaCl_2$) to the nutrient solution (Table 1). NaCl is the common salt in reclaimed water (Niu and Cabrera, 2010), whereas $CaCl_2$ is used to prevent potential calcium deficiencies (Carter and Grieve, 2006). The pH of all solutions was adjusted to 6.7 ± 0.1 using nitric acid (HNO_3). Both nutrient and saline solutions were prepared in 100-L tanks, with EC (Table 1) confirmed using an EC meter (LAQUA Twin; Horiba, Kyoto, Japan). Right after treatment solution was applied, leachate EC was determined using the pour-through protocol described by Cavins et al. (2008) and Wright (1986). The leachate EC , one plant per treatment per species, was measured using the EC meter and averaged across species. The substrate final EC_e was determined using a saturated soil paste technique (Gavlak et al., 1994).

During the entire experiment (13 Apr.–29 June 2018), the average air temperature in the greenhouse was $26.2 \pm 1.9\ ^{\circ}C$ during the day and $19.6 \pm 5.0\ ^{\circ}C$ at night, and the average daily light integral inside the greenhouse was

$17.5 \times 3.6\ mol\cdot m^{-2}\cdot d^{-1}$. Supplemental light at light intensities of $160 \pm 32\ \mu mol\cdot m^{-2}\cdot s^{-1}$ at the canopy level was provided using 1000-W high-pressure sodium lamps (Hydrofarm, Petaluma, CA) from 600 to 2200 HR , when light intensity inside the greenhouse was less than $544\ \mu mol\cdot m^{-2}\cdot s^{-1}$ from 13 Apr. to 2 May.

Foliar salt damage and plant growth. A reference scale (visual score) from 0 to 5, where 0 = dead, 1 = severe foliar damage ($>90\%$ leaves with burn and necrosis at the top part of leaf blade), 2 = moderate foliar damage (50% to 90%), 3 = slight foliar damage ($<50\%$), 4 = good quality with minimal foliar damage, and 5 = excellent with no foliar damage (Sun et al., 2015a) was used to rate foliar salt damage. Plant size was not considered during the evaluation of the foliar salt damage. On 29 June (65 d after the initiation of treatment), all plants were harvested as plant roots were heavily circled in 2-gal containers. Plant height (in centimeters) was recorded from the pot rim to the tip of the tallest leaf. The number of inflorescences and tillers was counted. Plant shoots were cut at the substrate surface, and leaf area was determined using an area meter (LI-3100; LI-COR[®] Biosciences, Lincoln, NE). Shoot dry weight was determined when plant shoots were dried in an oven at $70\ ^{\circ}C$ for 3 d.

Chlorophyll content and gas exchange. At harvest, soil-plant analysis development (SPAD) readings were taken from 10 fully expanded leaves on each plant using a handheld chlorophyll meter (SPAD 502 Plus; Minolta Camera Co., Osaka, Japan), and the average values was recorded for representing relative chlorophyll content. Fully expanded leaves at the top of at least six plants per treatment per species were measured 3 d before harvest for (P_n), g_s , and transpiration rate using a portable photosynthesis system with an automatic universal PLC6 broadleaf cuvette (CIRAS-3; PP Systems, Amesbury, MA). Data were recorded when the environmental conditions (leaf temperature, $25\ ^{\circ}C$; photosynthetic photon flux, $1000\ \mu mol\cdot m^{-2}\cdot s^{-1}$; and carbon dioxide concentration, $400\ \mu mol\cdot mol^{-1}$) and gas exchange parameters within the cuvette became stable. Gas exchange measurements were acquired on a sunny day between 1000 and 1400 HR , and plants were well watered to avoid water stress.

Mineral analyses. To analyze Na^+ , Cl^- , calcium (Ca^{2+}), and potassium (K^+) concentrations in leaves, four plants per ornamental grass species per treatment were selected randomly, and dried plant materials were ground to pass through a 40-mesh screen with a stainless Wiley mill (Thomas Scientific, Swedesboro, NJ). Powder samples were submitted to Texas A&M AgriLife Research Center (El Paso, TX) for Cl^- analyses and to the University of Texas (El Paso, TX) for macronutrient [Ca^{2+} , K^+ , magnesium (Mg^{2+}), phosphorus (P), and sulfur (S)] and micronutrients [Na^+ , zinc (Zn^{2+}), iron (Fe^{3+}), and manganese (Mn^{2+})] analyses. The powder samples were extracted using 2% acetic acid (Fisher Scientific, Fair Lawn, NJ) following the protocol described by Gavlak et al. (1994). The Cl^- concentration was determined

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Table 1. The chemical compositions of treatment solutions used in the experiment.

| Item | Tap water | Nutrient solution ^z (control) | Saline solution ^y | |
|-----------------------------------------------------|-----------|---------------------------------------------|------------------------------|-------------|
| | | | EC 5 | EC 10 |
| NaCl (g·L ⁻¹) | — | — | 0.92 | 2.27 |
| CaCl ₂ (g·L ⁻¹) | — | — | 0.88 | 2.18 |
| Ca ²⁺ (mg·L ⁻¹) | 47.2 | 82.5 | 362.5 | 759.8 |
| Mg ²⁺ (mg·L ⁻¹) | 17.3 | 27.6 | 29.1 | 30.9 |
| Na ⁺ (mg·L ⁻¹) | 1.4 | 0.4 | 359.6 | 872.4 |
| SO ₄ ²⁻ (mg·L ⁻¹) | 8.9 | 11.2 | 11.2 | 11 |
| Cl ⁻ (mg·L ⁻¹) | 3.4 | 5.7 | 1,050 | 2,780 |
| B ³⁺ (mg·L ⁻¹) | 0 | 0.23 | 0.22 | 0.2 |
| Sodium adsorption ratio (SAR) | 0.04 | 0.07 | 4.88 | 8.42 |
| Adjusted SAR | 0.09 | 0.13 | 11.2 | 20.9 |
| EC (dS·m ⁻¹) | 0.37 | 1.21 ± 0.07 | 4.99 ± 0.09 | 9.89 ± 0.27 |

^zA nutrient solution at an electrical conductivity (EC) of 1.2 dS·m⁻¹ (control) was prepared by adding 0.8 g·L⁻¹ 15N–2.2P–12.5K water-soluble fertilizer (Peters Excel 15–5–15 Ca-Mag Special; ICL Specialty Fertilizers, Dublin, OH) to tap water.

^ySaline solution at an EC of 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10) was created by adding sodium chloride (NaCl) and calcium chloride (CaCl₂) to the nutrient solution.

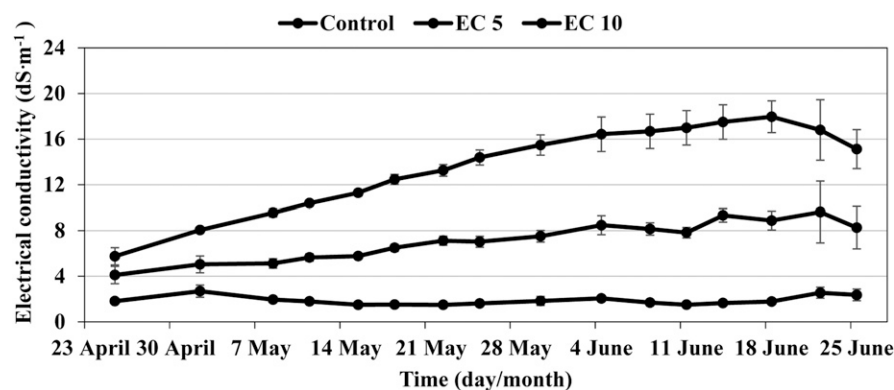


Fig. 1. Time course of the electrical conductivity (EC) of leachate solution collected after ornamental grasses were irrigated with a nutrient solution at an EC of 1.2 dS·m⁻¹ (control), or a saline solution at an EC of 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10) in a greenhouse. Saline solution was created by adding sodium chloride and calcium chloride to the nutrient solution. Vertical bars represent ses of four measurements, one plant per treatment per ornamental grass species.

using a chloride analyzer (M926; Cole Parmer Instrument Company, Vernon Hills, IL) and is reported on a dry plant basis (as milligrams per gram). At the University of Texas at El Paso, powder samples (~0.2 g) were digested in 2.5 mL of plasma pure HNO₃ (SCP Science, Champlain, NY) that were incubated in a Digiprep hot block (SCP Science) at 115 °C for 45 min until samples were totally dissolved. If undigested material remained, 1 mL 30% hydrogen peroxide was added and the samples were returned to incubation for additional 20 min. The digested solutions were adjusted to 45 mL with millipore water. Macronutrients (Ca²⁺, K⁺, Mg²⁺, P, and S) and micronutrients (Na⁺, Zn²⁺, Fe³⁺, and Mn²⁺) were measured by inductively coupled plasma–optical emission spectrometry (ICP-OES, Perkin-Elmer Optima 4300 DV; Perkin-Elmer, Shelton, CT), and are reported on a dry plant basis (in milligrams per gram). To validate the measurements, a blank (no plant tissues) and standard reference material (Spinach, 1570a; National Institute of Standards and Technology, Gaithersburg, MD) were also analyzed in ICP-OES after every 20 samples.

Experimental design and statistical analysis. The experiment used a completely randomized design with 10 plants per treatment

per species. Two-way analysis of variance was performed for all plant growth parameters. Visual score was analyzed as multinomial data, whereas number of inflorescences and tillers were analyzed as negative binomial data. Means separation among treatments and species was adjusted using Tukey's method for multiplicity at $\alpha = 0.05$. All statistical analyses were performed with the GENMOD and GLIMMIX procedures of SAS/STAT 14.3 in SAS (version 9.4; SAS Institute, Cary, NC).

Results and Discussion

Because ornamental grasses were irrigated with saline solution, the salinity in the leachate solution gradually increased (Fig. 1). Throughout the entire experiment, the EC of the leachate solution was around 1.9 dS·m⁻¹ for the control. Starting from the second irrigation, with saline solution at an EC of 5.0 or 10.0 dS·m⁻¹, the EC of the leachate solution was consistently greater than the control (all P values < 0.0045). The EC of the leachate solution increased from 4.1 to 9.6 dS·m⁻¹ and from 5.8 to 18.0 dS·m⁻¹ when irrigated with saline solution at an EC of 5.0 and 10.0 dS·m⁻¹, respectively. These results indicate that salts accumulated

in the growing substrate, which can be seen in the final soil ECe, which was measured using a saturated soil paste technique (Table 2, Fig. 2). After 16 irrigations with saline solution at an EC of 5.0 dS·m⁻¹, the soil ECe values were 8.2, 12.7, 12.5, and 8.6 dS·m⁻¹ for *E. spectabilis*, *M. sinensis*, *P. virgatum*, and *S. scoparium*, respectively (Fig. 2); saline solution at an EC of 10.0 dS·m⁻¹ further increased the soil ECe to 15.7, 22.1, 22.5, and 21.9 dS·m⁻¹, respectively (Fig. 2).

Saline solution irrigation affected plant visual quality, with different responses among ornamental grass species (Table 2). *Panicum virgatum* and *S. scoparium* exhibited no foliar salt damage when irrigated with saline solution at an EC of 5.0 or 10.0 dS·m⁻¹ (Table 3). *Eragrostis spectabilis* showed minimal foliar salt damage when irrigated with saline solution at an EC of 5.0 dS·m⁻¹, but had slight foliar salt damage, with an average visual score of 3.6 when irrigated with saline solution at an EC of 10.0 dS·m⁻¹. *Miscanthus sinensis* displayed slight foliar salt damage, with average visual scores of 3.7 and 3.3, respectively, when irrigated with saline solution at an EC of 5.0 or 10.0 dS·m⁻¹. These results indicate that four ornamental grasses had a strong tolerance to the salinity levels tested in this study. Similarly, *Muhlenbergia lindheimeri* Hitchc. (blue muhly grass) had an acceptable visual quality when they were grown for 8 weeks in a hydroponic system with saline solution at an EC of 5.0 or 10.0 dS·m⁻¹ achieved by the addition of a 2:1 ratio of NaCl to CaCl₂ in half-strength Hoagland solution (McKenney et al., 2016). In a previous study, sand ryegrass, pink muhly grass, and fountain grass irrigated with saline solution at an EC of 5.0 or 10 dS·m⁻¹ for 18 weeks also had a good visual quality, with minimal foliar salt damage (Sun and Palmer, 2018).

Saline solution irrigation affected plant height and leaf area, but there were no interactive effects between salt treatment and ornamental grass species (Table 2). Regardless of species, all ornamental grasses irrigated with saline solution at an EC of 5.0 dS·m⁻¹ had a similar height to the control (Fig. 3A); however, ornamental grasses were 15% shorter than the control when irrigated with saline solution at an EC of 10.0 dS·m⁻¹. The leaf area of all ornamental grasses irrigated with saline solution at an EC of 5.0 or 10.0 dS·m⁻¹ decreased by 22% and 47%, respectively, compared with the control (Fig. 3B). These results are in line with previous reports that salinity stress inhibited plant growth and leaf expansion (Sun and Palmer, 2018; Sun et al., 2015a; Wu et al., 2016). For example, all ornamental grass and grasslike plants irrigated with saline solution at an EC of 10.0 dS·m⁻¹ were 10% to 38% shorter than the control at 9 weeks after the initiation of treatment, but they had a similar height to the control when irrigated with saline solution at an EC of 5.0 dS·m⁻¹, except *Chasmanthium latifolium* (Michx.) Yates (indian sea oats), pink muhly grass, and fountain grass (Sun and Palmer, 2018). Plant

Table 2. A summary of analysis of variance for the effects of irrigation water electrical conductivity (EC), plant species, and their interactions on saturated soil extract (EC_e), plant visual score, height, leaf area, number of inflorescences, number of tillers, shoot dry weight (DW), relative chlorophyll content [soil–plant analysis development (SPAD) reading], net photosynthesis rate (P_n), stomatal conductance (g_s), and transpiration rate (E) of ornamental grasses irrigated with a nutrient solution at an EC of 1.2 dS·m⁻¹ (control), or a saline solution at an EC of 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10) in a greenhouse.²

| Source | Analysis of variance | | | | | | | | | | |
|--------------|-----------------------------------|--------------|-----|-----------|---------------------|--------------|----------|------|----------------|----------------|-----|
| | Soil EC _e ^y | Visual score | Ht | Leaf area | Inflorescence (no.) | Tiller (no.) | Shoot DW | SPAD | P _n | g _s | E |
| EC | *** | *** | *** | *** | *** | *** | *** | *** | ** | *** | *** |
| Species | *** | *** | *** | *** | *** | *** | *** | * | *** | *** | *** |
| EC × species | * | *** | NS | NS | * | ** | NS | ** | * | * | NS |

²Saline solution was created by adding sodium chloride (NaCl) and calcium chloride (CaCl₂) to the nutrient solution.

^ySoil EC_e was collected using a saturated soil paste technique (Gavlak et al., 1994).

NS, *, **, ***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

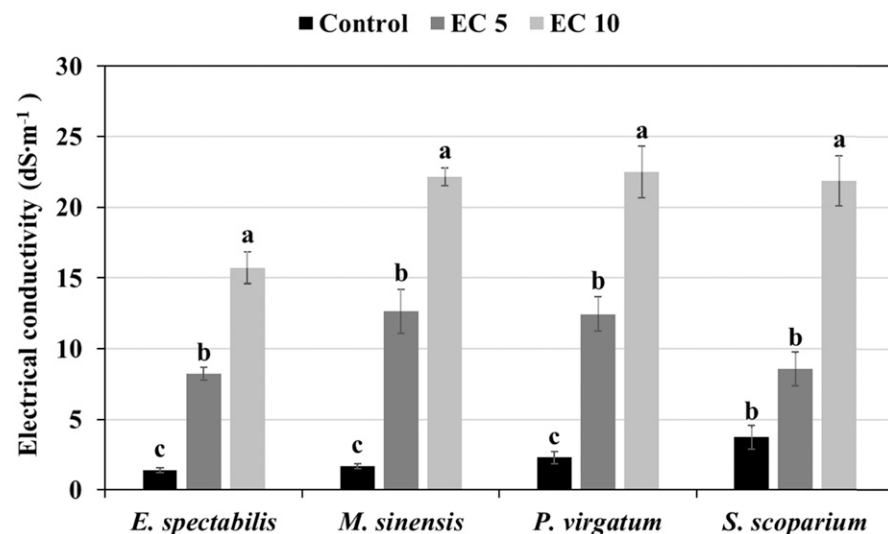


Fig. 2. Electrical conductivity (EC) of the substrate used for growing ornamental grasses. Plants were irrigated roughly every 4 d with a nutrient solution at an EC of 1.2 dS·m⁻¹ (control), or a saline solution at an EC of 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10). A saturated soil paste technique (Gavlak et al., 1994) was used to determine the saturated soil extract of the growing substrate. Vertical bars represent SEs of three replications.

height of blue muhly grass and *Carex tumulicola* Mack. (foothill sedge) were barely affected by increasing salinity until an EC of 5.0 dS·m⁻¹, but declined significantly at an EC of 10.0 dS·m⁻¹ at 8 weeks of exposure to saline water in a hydroponic system (McKenney et al., 2016). Saline solution at an EC of 10.0 dS·m⁻¹ also reduced the leaf area of indian sea oats, *Juncus effusus* L. (common rush), and fountain grass at 9 weeks after the initiation of treatment (Sun and Palmer, 2018). This is one of the adaptation strategies against salt-induced water deficit, during which plants reduce plant growth and leaf expansion to prevent water loss.

Saline solution irrigation influenced the number of inflorescences and tillers with varying responses among ornamental grass species (Table 2). No *M. sinensis* plants flowered during the entire experimental period (Table 3). Compared with the control, the number of inflorescences of *E. spectabilis* and *P. virgatum* reduced by 34% and 29%, respectively, when irrigated with saline solution at an EC of 5.0 dS·m⁻¹; and by 40% and 59%, respectively, when irrigated with saline solution at an EC of 10.0 dS·m⁻¹. However, there was no significance among treatments for the number of inflorescences of *S. scoparium*. Increasing salinity stress has been observed to affect the flowering of ornamen-

tal grasses negatively (Scheiber et al., 2008; Sun and Palmer, 2018). Saline solution at an EC of 5.0 or 10.0 dS·m⁻¹ reduced the number of tillers of *E. spectabilis* by 27% and 40%, respectively, compared with the control (Table 3). Saline solution at an EC of 10.0 dS·m⁻¹ also decreased the number of tillers of *S. scoparium* by 52%, but this was not the case for *M. sinensis* and *P. virgatum*, which tended to have less tillers. In a previous study, *Carex vulpinoidea* Michx. (fox sedge) and fountain grass produced 26% and 23% fewer tillers, respectively, compared with the control, when irrigated with saline solution at an EC of 10.0 dS·m⁻¹ for 18 weeks (Sun and Palmer, 2018). However, this saline water irrigation slightly reduced the number of tillers of blue grama, 'Blue Dune' sand ryegrass, indian sea oats, common rush, and pink muhly grass.

Saline solution irrigation had a significant effect on the shoot dry weight, and all ornamental grass species showed similar responses to salt treatments (Table 2). Regardless of species, the shoot dry weight of all ornamental grasses reduced by 25% and 46% when irrigated with saline solution at an EC of 5.0 or 10.0 dS·m⁻¹, respectively, compared with the control (Fig. 4A). In addition, *E. spectabilis* and *M. sinensis* produced the greatest shoot dry weight, but *S. scoparium* accumulated the least (Fig. 4A). It was not

surprising to see this result because previous studies have observed that increasing salinity stress inhibited plant growth and development of ornamental grasses significantly (Alvarez, 2006; LeCompte et al., 2016; Zhang et al., 2012).

Saline solution irrigation affected the relative chlorophyll content (SPAD reading) (Tables 2 and 4). The SPAD readings of *E. spectabilis* and *S. scoparium* were not significant among treatments. Saline solution at an EC of 10.0 dS·m⁻¹ reduced the SPAD readings of *M. sinensis* by 11%. This result is similar to the findings observed by Sun et al. (2015b): The SPAD reading of a wild *M. sinensis* population decreased with increasing NaCl concentrations and stress duration. Salinity may inhibit chlorophyll synthesis and/or accelerate its degradation (Netondo et al., 2004; Zhao et al., 2007). *Panicum virgatum* irrigated with saline solution at an EC of 5.0 and 10.0 dS·m⁻¹ had an increase of 10% and 6% in the SPAD readings, respectively. This is also true for switchgrass cultivars evaluated previously (Sun et al., 2018).

Saline solution irrigation had a significant influence on the leaf P_n and g_s of ornamental grasses, and varying responses were observed among ornamental grass species (Table 2). Leaf P_n of *E. spectabilis* and *P. virgatum* irrigated with saline solution at an EC of 10.0 dS·m⁻¹ decreased by 49% and 36%, respectively, compared with the control, but this was not the case for those irrigated with saline solution at an EC of 5.0 dS·m⁻¹ (Table 4). When irrigated with saline solution at an EC of 5.0 and 10.0 dS·m⁻¹, the P_n of *M. sinensis* reduced by 31% and 36%, respectively, and that of *S. scoparium* decreased by 32% and 60%, respectively, compared with the control. Salinity stress has been documented to inhibit plant photosynthesis. Sun et al. (2015b) reported that *M. sinensis* plants irrigated with saline solution at an EC of 6.1, 10.5, 23.6, and 27.0 dS·m⁻¹ had a decrease of 21%, 35%, 61%, and 79% in photosynthesis, respectively, for accession JM0119; and 26%, 47%, 72%, and 89%, respectively, for accession JM0099. This is similar to our results, although 20N–8.8P–16.6K fertilizer solutions containing NaCl and CaCl₂ at a 5:1-M ratio were used for irrigating *M. sinensis* plants daily for 30 d. *P. virgatum* tolerant lines showed about 50% reduction in photosynthesis, and sensitive lines exhibited about 90% reduction after being irrigated for 30 d with 250 mM NaCl solution (EC, ≈21 dS·m⁻¹) (Kim et al., 2016). Saline solution irrigation

Table 3. Visual score, number of inflorescences, and number of tillers of ornamental grasses irrigated with a nutrient solution at an electrical conductivity (EC) of 1.2 dS·m⁻¹ (control), or a saline solution at an EC of 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10) in a greenhouse.^z

| Species | Visual score ^y | | | Inflorescence (no.) | | | Tiller (no.) | | |
|-----------------------|---------------------------------|--------|--------|---------------------|---------|---------|--------------|----------|---------|
| | Control | EC 5 | EC 10 | Control | EC 5 | EC 10 | Control | EC 5 | EC 10 |
| <i>E. spectabilis</i> | 5.0 a ^A ^w | 4.7 aA | 3.6 bB | 81.1 aA | 53.8 bA | 48.7 bA | 96.1 aAB | 70.2 bB | 58.0 bA |
| <i>M. sinensis</i> | 5.0 aA | 3.7 bB | 3.3 cB | — ^v | — | — | 90.2 aAB | 70.6 aB | 75.7 aA |
| <i>P. virgatum</i> | 5.0 aA | 5.0 aA | 5.0 aA | 24.1 aB | 17.1 bB | 9.9 cB | 72.6 aB | 61.5 aB | 59.0 aA |
| <i>S. scoparium</i> | 5.0 aA | 5.0 aA | 5.0 aA | 13.1 aB | 11.6 aB | 9.2 aB | 116.3 aA | 101.4 aA | 55.3 bA |

^zSaline solution was created by adding sodium chloride (NaCl) and calcium chloride (CaCl₂) to the nutrient solution. Plants were harvested after the sixteenth irrigation (65 d after the initiation of treatment).

^y0 = dead; 1 = severe foliar salt damage (>90% leaves with burn and necrosis at the top part of leaf blade); 2 = moderate (50% to 90%) foliar salt damage; 3 = slight (<50%) foliar salt damage; 4 = good quality with minimal foliar salt damage; and 5 = excellent without foliar salt damage (Sun et al., 2015a).

^xMeans with the same lowercase letters within a row and a dependent variable are not significantly different among treatments by Tukey's method for multiplicity at $\alpha = 0.05$.

^wMeans with the same uppercase letters within a column are not significantly different among species by Tukey's method for multiplicity at $\alpha = 0.05$.

^vNo plants flowered during the entire experimental period.

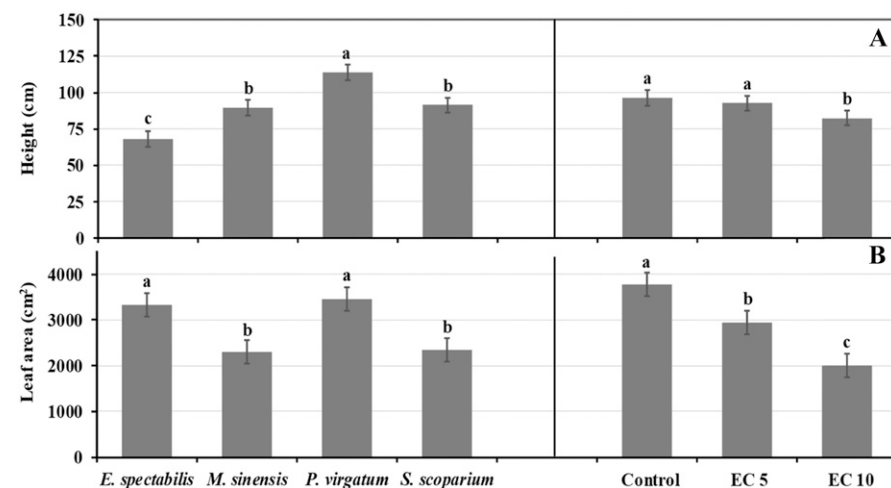


Fig. 3. Plant height (A) and leaf area (B) of ornamental grasses irrigated with a nutrient solution at an electrical conductivity (EC) of 1.2 dS·m⁻¹ (control), or a saline solution at an EC of 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10) in a greenhouse. Saline solution was created by adding sodium chloride and calcium chloride to the nutrient solution. Plants were harvested after the 16th irrigation (65 d after the initiation of treatment). Vertical bars represent SEM of 10 replications.

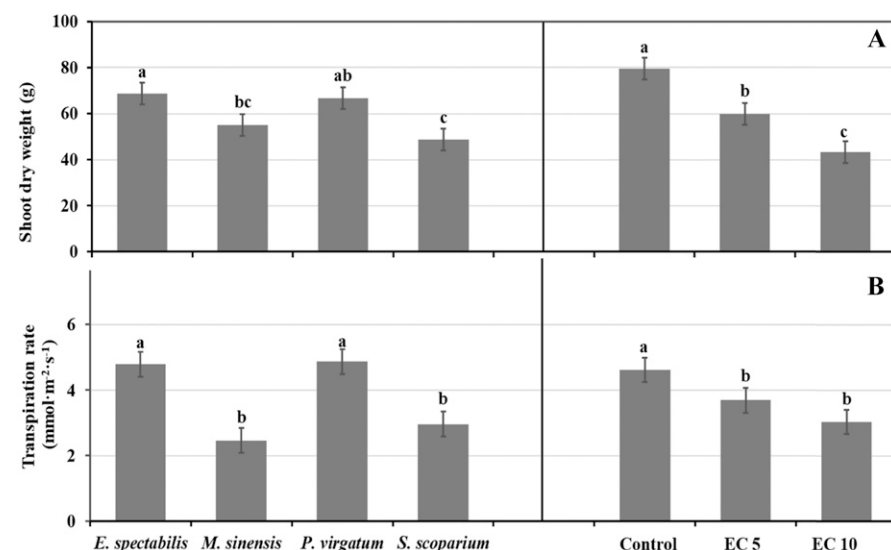


Fig. 4. Shoot dry weight (A) and transpiration rate (B) of ornamental grasses irrigated with a nutrient solution at an electrical conductivity (EC) of 1.2 dS·m⁻¹ (control), or a saline solution at an EC of 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10) in a greenhouse. Saline solution was created by adding sodium chloride and calcium chloride to the nutrient solution. Plants were harvested after the 16th irrigation (65 d after the initiation of treatment). Vertical bars represent SEM of 10 and 6 measurements for shoot dry weight and transpiration rate, respectively.

did not affect the g_s of *P. virgatum* (Table 4). The g_s of *M. sinensis* and *S. scoparium* plants irrigated with saline solution at an EC of 5.0 dS·m⁻¹ decreased by 44% and 37%, respectively; and that of *E. spectabilis*, *M. sinensis*, and *S. scoparium* plants irrigated with saline solution at an EC of 10.0 dS·m⁻¹ decreased by 59%, 42%, and 62%, respectively, compared with the control. Sun et al. (2015b) also observed that salinity stress strongly reduced the g_s of *M. sinensis* accessions (JM0119 and JM0099). Saline solution irrigation affected leaf transpiration rate of ornamental grasses, but no interactive effect was detected between ornamental grass species and the EC level of saline solution (Table 2). Regardless of ornamental grass species, all plants irrigated with saline solution at an EC of 5.0 and 10.0 dS·m⁻¹ had 34% and 20% reduction in the transpiration rate, respectively, compared with the control (Fig. 4B). When the salt-induced water deficit continues to increase, stomatal closure occurs and transpiration decreases.

Mineral analyses. The Na⁺ and Cl⁻ concentrations in the leaf tissue of ornamental grasses were affected by increasing salinity levels, and also varied among ornamental grass species (Table 5). Along with increasing salinity, *M. sinensis* accumulated the greatest amount of Na⁺ ions, whereas *S. scoparium* took up the least. Compared with the control, the leaf Na⁺ concentration of *E. spectabilis*, *M. sinensis*, *P. virgatum*, and *S. scoparium* increased 4.0, 18.8, 4.5, and 1.6 times, respectively, when irrigated with saline solution at an EC of 5.0 dS·m⁻¹; and increased 14.3, 52.6, 5.3, and 1.7 times, respectively, when irrigated with saline solution at an EC of 10.0 dS·m⁻¹. The fact that leaf Na⁺ concentration increased with increasing salinity levels of irrigation water has been observed previously. *M. sinensis* (accession JM0099) grown in peatmoss and irrigated with saline solution at an EC of 3.2, 6.1, and 10.5 dS·m⁻¹ for 30 d in a greenhouse accumulated about 4.6, 6.9, and 12.7 mg·g⁻¹ Na⁺ in the leaves (Sun et al., 2015b). Switchgrass cultivars grown in a high-porosity growing mix (3 peatmoss:2 perlite) and watered with saline solution at an EC of 5.0 and 10.0 dS·m⁻¹ for 4 weeks had 0.5 to 1.6 mg·g⁻¹ Na⁺ in the leaves (Sun et al., 2018). The values documented in these reports are similar to the leaf Na⁺ concentrations of *M. sinensis* and *P.*

Table 4. Relative chlorophyll content [soil–plant analysis development (SPAD) reading], leaf net photosynthesis rate (P_n), and stomatal conductance (g_s) of ornamental grasses irrigated with a nutrient solution at an electrical conductivity (EC) of 1.2 dS·m⁻¹ (control), or a saline solution at an EC of 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10) in a greenhouse.^z

| Species | SPAD | | | P_n (μmol·m ⁻² ·s ⁻¹) | | | g_s (mmol·m ⁻² ·s ⁻¹) | | |
|-----------------------|------------------------------------|---------|----------|------------------------------------------------|-----------|---------|------------------------------------------------|-----------|----------|
| | Control | EC 5 | EC 10 | Control | EC 5 | EC 10 | Control | EC 5 | EC 10 |
| <i>E. spectabilis</i> | 53.0 a ^y A ^x | 52.8 aA | 51.5 aA | 17.9 aA | 14.4 abAB | 9.2 bA | 276.0 aA | 180.7 abA | 113.7 bA |
| <i>M. sinensis</i> | 30.6 abD | 31.7 aD | 27.3 bD | 14.3 aA | 9.8 bC | 9.1 bA | 168.5 aB | 93.8 bB | 97.8 bA |
| <i>P. virgatum</i> | 39.9 bC | 43.7 aC | 42.5 abC | 16.7 aA | 16.3 aA | 10.7 bA | 162.9 aB | 172.7 aA | 105.2 aA |
| <i>S. scoparium</i> | 46.5 aB | 47.9 aB | 49.2 aB | 18.7 aA | 12.8 bBC | 7.5 cA | 172.5 aB | 108.2 bAB | 65.0 bA |

^zSaline solution was created by adding sodium chloride (NaCl) and calcium chloride (CaCl₂) to the nutrient solution. Plants were harvested after the sixteenth irrigation (65 d after the initiation of treatment).

^yMeans with the same lowercase letters within a row and a dependent variable are not significantly different among treatments by Tukey's method for multiplicity at $\alpha = 0.05$.

^xMeans with the same uppercase letters within a column are not significantly different among species by Tukey's method for multiplicity at $\alpha = 0.05$.

Table 5. Macronutrients and micronutrients of ornamental grasses irrigated with a nutrient solution at an electrical conductivity (EC) of 1.2 dS·m⁻¹ (control), or a saline solution at an EC of 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10) in a greenhouse.^z

| Species | Treatment | Mineral concn (mg·g ⁻¹ dry wt) | | | | | |
|-----------------------|-----------|-------------------------------------------|-----------------|------------------|----------------|------------------|------------------|
| | | Na ⁺ | Cl ⁻ | Ca ²⁺ | K ⁺ | Mg ²⁺ | Mn ²⁺ |
| <i>E. spectabilis</i> | Control | 0.28 b ^y | 2.06 c | 4.19 b | 18.42 a | 2.92 a | 0.06 b |
| | EC 5 | 1.41 b | 10.81 b | 5.48 b | 15.37 a | 2.57 ab | 0.08 ab |
| | EC 10 | 4.33 a | 21.35 a | 9.39 a | 14.70 a | 2.52 b | 0.10 a |
| <i>M. sinensis</i> | Control | 0.18 c | 2.62 c | 3.99 b | 21.37 a | 3.17 a | 0.02 a |
| | EC 5 | 3.47 b | 16.29 b | 6.57 b | 17.14 b | 3.00 a | 0.02 a |
| | EC 10 | 9.37 a | 31.59 a | 12.22 a | 15.44 b | 2.73 a | 0.03 a |
| <i>P. virgatum</i> | Control | 0.23 b | 2.68 b | 2.52 a | 21.73 a | 3.12 a | 0.02 a |
| | EC 5 | 1.25 ab | 9.68 a | 2.92 a | 18.17 a | 2.32 b | 0.03 a |
| | EC 10 | 1.43 a | 10.14 a | 3.48 a | 19.55 a | 2.10 b | 0.03 a |
| <i>S. scoparium</i> | Control | 0.43 b | 2.78 b | 2.53 b | 20.28 a | 2.26 a | 0.03 a |
| | EC 5 | 1.14 a | 8.35 a | 5.72 a | 16.98 b | 2.30 a | 0.03 a |
| | EC 10 | 1.17 a | 10.31 a | 7.23 a | 14.65 b | 2.01 a | 0.03 a |
| Species | | *** | *** | *** | *** | *** | *** |
| Treatment | | *** | *** | *** | *** | ** | *** |
| Species × treatment | | *** | *** | ** | NS | NS | * |

^zSaline solution was created by adding sodium chloride (NaCl) and calcium chloride (CaCl₂) to the nutrient solution. Plants were harvested after the 16th irrigation (65 d after the initiation of treatment).

^yWithin species, means with the same lowercase letters within a column and a dependent variable are not significantly different among treatments by Tukey's method for multiplicity at $\alpha = 0.05$.

NS, *, **, ***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

virgatum in our study, although different growing substrates and varied durations of saline solution application were used. To the best of our knowledge, there were no reports of the leaf Na⁺ concentrations of *E. spectabilis* and *S. scoparium* irrigated with saline water irrigation. However, the values recorded in our study were much less than those reported by LeCompte et al. (2016), who found that pink muhly grass had 11.7 to 31.4 mg·g⁻¹ Na⁺ in the leaves when grown in a substrate (5 pinebark:3 peat:1 perlite) and irrigated with 4000 to 10,000 mg·L⁻¹ NaCl (≈5.0–12.5 dS·m⁻¹) for 15 weeks. The discrepancy in the leaf Na⁺ concentrations in these studies might result from different plant species and different durations of saline water irrigation.

Compared with the control, *E. spectabilis*, *M. sinensis*, *P. virgatum*, and *S. scoparium* had 4.3, 5.2, 2.6, and 2.0 times more Cl⁻ ions in the leaves, respectively, when irrigated with saline solution at an EC of 5.0 dS·m⁻¹ (Table 5). The Cl⁻ concentration in the leaf tissue of *E. spectabilis*, *M. sinensis*, *P. virgatum*, and *S. scoparium* increased an additional 9.4, 11.1, 2.8, and 2.7 times, respectively, when irrigated with saline solution at an EC of 10.0 dS·m⁻¹. Sun et al. (2018) reported that switchgrass irrigated with saline solution at an EC of 5.0 and 10.0 dS·m⁻¹ accumulated about 10.8 to 13.5 and 12.7 to 15.3 mg·g⁻¹ Cl⁻ ions in the leaves, respectively.

Pink muhly grass irrigated with 2000 to 4000 mg·L⁻¹ NaCl (EC, ≈2.5–5.0 dS·m⁻¹) had 15.6 to 17.4 mg·g⁻¹ Cl⁻ ions in the leaves (LeCompte et al., 2016). These values are similar to or slightly greater than our results. *M. sinensis* (accession JM0099) watered with saline solution at an EC of 3.2, 6.1, and 10.5 dS·m⁻¹ accumulated about 28.4, 32.0, and 49.7 mg·g⁻¹ Cl⁻ ions in the leaves (Sun et al., 2015b), whereas pink muhly grass irrigated with 6000 to 10,000 mg·L⁻¹ NaCl (EC, ≈7.5–12.5 dS·m⁻¹) had 47.6 to 60.7 mg·g⁻¹ Cl⁻ ions in the leaves (LeCompte et al., 2016). The values in these studies are much greater than our observations. Factors such as duration of saline water irrigation and plant species contributed to the differences in leaf Cl⁻ concentration.

Although leaf Na⁺ and Cl⁻ concentrations correlated negatively with visual score ($P < 0.0001$), all ornamental grass species still exhibited a good visual quality. Both leaf Na⁺ and Cl⁻ concentrations also correlated negatively with leaf area ($P = 0.05$ and 0.02, respectively) and shoot dry weight ($P = 0.08$ and 0.03, respectively), but not with plant height and number of tillers. These results indicate that leaf Na⁺ and Cl⁻ concentrations are still not high enough to cause salt damage to the ornamental grasses. It might be also true that these four ornamental grass species can tolerate the levels of Na⁺ and Cl⁻ ions or

even greater in the leaves. In this case, osmotic effects might have the most influences on plant growth and development (Munns and Tester, 2008). High Na⁺ and/or Cl⁻ accumulation in leaf tissue has been reported to damage the chloroplasts and inhibit photosynthesis (Taiz and Zeiger, 2015). Both leaf Na⁺ and Cl⁻ concentrations correlated negatively with P_n ($P = 0.02$ and 0.004, respectively), transpiration rate ($P = 0.02$ and 0.01, respectively), and g_s ($P = 0.06$ and 0.02, respectively), but not with SPAD. The Na⁺ and Cl⁻ concentrations in these ornamental grass species are high enough to inhibit plant photosynthesis.

The leaf Ca²⁺ concentrations of ornamental grasses were affected interactively by increasing salinity levels and ornamental grass species (Table 5). *Schizachyrium scoparium* accumulated 126% more Ca²⁺ ions in the leaves than the control when they were irrigated with saline solution at an EC of 5.0 dS·m⁻¹, but this was not the case for the other three species (Table 5). All ornamental grass species irrigated with saline solution at an EC of 10.0 dS·m⁻¹ had one or two times more Ca²⁺ ions in the leaves than the control, with the exception of *P. virgatum*. Although CaCl₂ is one of the components in the saline solution used in our study, the increase of the Ca²⁺ levels in the leaves was relatively small,

which could result from selective uptake of Na^+ ions by ornamental grasses. Sun et al. (2018) reported that leaf Ca^{2+} concentration of six switchgrass cultivars watered with saline solution at an EC of 5.0 and 10.0 $\text{dS}\cdot\text{m}^{-1}$ ranged from 4.4 to 6.4 $\text{mg}\cdot\text{g}^{-1}$, which is similar to the results in this study. However, pink muhly grass irrigated with 2000 to 10,000 $\text{mg}\cdot\text{L}^{-1}$ NaCl (EC, ≈ 2.5 –12.5 $\text{dS}\cdot\text{m}^{-1}$) had 1.1 to 1.8 $\text{mg}\cdot\text{g}^{-1}$ Ca^{2+} in the leaves (LeCompte et al., 2016), which is much less than our results. Salinity dominated by sodium salts decreases the availability, transport, and mobility of Ca^{2+} to plant growth and may cause Ca^{2+} deficiency (Grattan and Grieve, 1999). It is better to add CaCl_2 to the irrigation solution to avoid Ca^{2+} deficiency when salinity stress with sodium salts exists.

Increasing salinity affected the K^+ concentrations in the leaves of ornamental grasses (Table 5). Regardless of ornamental grass species, saline solution at an EC of 5.0 and 10.0 $\text{dS}\cdot\text{m}^{-1}$ decreased the K^+ concentration by 17% and 21%, respectively, compared with the control. This result is in line with previous observations on the leaf K^+ concentration of switchgrass cultivars (Sun et al., 2018) and *M. sinensis* accessions (Sun et al., 2015b), but not for pink muhly grass (LeCompte et al., 2016). High sodium salts have competitive effects on K^+ acquisition—a mechanism of osmotic adjustment for plants to protect themselves from salt stress (Grattan and Grieve, 1999; Taiz and Zeiger, 2015).

Increasing salinity also affected the Mg^{2+} , Zn^{2+} , and Mn^{2+} concentrations in the leaves of ornamental grasses (Table 5). Regardless of ornamental grass species, saline solution at an EC of 5.0 and 10.0 $\text{dS}\cdot\text{m}^{-1}$ decreased the Mg^{2+} concentration by 11% and 18%, respectively, compared with the control. However, no significance in the leaf Mg^{2+} concentration was observed in pink muhly grass (LeCompte et al., 2016). On average, saline solution at an EC of 5.0 and 10.0 $\text{dS}\cdot\text{m}^{-1}$ increased the Zn^{2+} concentration by 19% and 34%, respectively, and Mn^{2+} concentration by 113% and 154%, respectively, compared with the control. Increasing salinity did not affect the P, S, and Fe^{3+} concentration in the leaves of all tested ornamental grasses (data not shown). However, leaf P concentrations in pink muhly grass increased linearly with increasing NaCl concentrations (LeCompte et al., 2016). Excessive Na^+ and Cl^- uptake has been observed to induce mineral nutrient imbalance, resulting in nutritional disorders and reduced plant quality (Grattan and Grieve, 1999). The concentrations of those mineral nutrients were still in the normal range as no obvious symptoms of nutrient deficiency were observed in our study.

In conclusion, plant growth and photosynthesis of all four ornamental grasses reduced, to some extent, as a result of saline water irrigation. Minimum foliar salt damage on *P. virgatum* and *S. scoparium* and slight foliar salt damage on *E. spectabilis* and *M. sinensis* were observed. Although high levels of Na^+ and Cl^- accumulated in the leaves of ornamental grasses, all plants were of acceptable visual quality and were considered marketable. Four ornamental grasses showed

a very strong tolerance to saline irrigation water containing NaCl and CaCl_2 salts in this research. Further study should be conducted during multiple growing seasons to assess plant growth and survival of all ornamental grasses in landscapes where saline irrigation water is used as well as in landscapes in salt-prone areas and nearby coastal regions.

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