Silicon Effects on *Poa pratensis* Responses to Salinity

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Abstract. Understanding turfgrass response to silicon (Si) application under salinity conditions is important to find a way to improve turfgrass salt tolerance for turf management. The objective of the study was to investigate effects of increasing amendment concentrations of Na₂SiO₃ on turf growth and distribution of Na⁺ and K⁺ in seedlings of kentucky bluegrass (KBG) (*Poa pratensis* L.) under salinity stress. This growth chamber experiment was consisted of a control (no salinity and no Si) and five Si amendment treatments (0, 0.24, 0.48, 0.72, and 0.96 g Si/kg saline soil) under 10 g·kg⁻¹ salinity conditions. Seed germination rate was significantly increased after 12 d under 0.48 g·kg⁻¹ Si treatment. Plant height and canopy coverage were increased under 0.72 g·kg⁻¹ Si treatment after 40 and 44 d of treatment, respectively, and tiller number was increased under 0.96 g·kg⁻¹ Si treatment compared with 0 Si under saline conditions. With the supplement of Si at 0.48 to 0.96 g·kg⁻¹, the ratio of Na⁺/K⁺ in shoots was decreased and individual leaf area was increased compared with 0 Si under saline conditions. The increase in individual leaf area was mainly the result of the increase in the leaf blade length. The concentration of K⁺ in shoots was significantly increased, whereas the concentrations of Na⁺ in roots were significantly decreased under all Si amendment treatments. The content of K⁺ was higher in shoots than in roots, but the ratio of Na⁺/K⁺ in roots was higher than in shoots in all Si amendment treatments. The results indicate that under saline conditions, Si induced the transfer of K⁺ from roots to shoots but inhibited the absorption and transfer of Na⁺, which may contribute to better turf quality and growth with Si treatment under saline conditions.

Salinity has been recognized as a major factor limiting crop productivity in many areas of the arid regions of the world where soil salt content is naturally high and precipitation is insufficient for leaching (Chinnusamy et al., 2005; Flowers, 2004; Matoh et al., 1988). In particular, turfgrass species are increasingly grown on soils plagued by accelerated urban development where salinity problems may develop from the use of saline irrigation water (Qian et al., 2001). KBG is

a widely used cool-season turfgrass in cool climatic regions (Beard, 1973; Erusha et al., 2002) and is considered to be salt-sensitive because it has been reported to tolerate less than 4 dS·m⁻¹ soil salinity (Qian et al., 2001). The effect of salinity on KBG growth is a complex syndrome that may result from osmotic stress, ion toxicity, and mineral deficiencies (Zhang et al., 2004). Osmotic stress is effective in the beginning (hours to few days) of exposure to salt, and ion toxicity becomes important in affecting plant growth after prolonged exposure (Munns, 1993, 2002).

Si is not considered to be an essential element for plant growth (Crusciol et al., 2009; Epstein, 1994, 1999), but there have been reports of interactions between Si supply and the responses of members of *Poaceae* to salinity stress (Dai et al., 2005; Liang, 1999). Ample evidence is presented that Si, when readily available to plants, had positive effects on plant growth under optimal conditions regarding mineral nutrition, mechanical strength, resistance to fungal diseases, and adverse chemical conditions of the growing

medium (Epstein, 1994; Winslow, 1992). Previous studies have shown that supplementing the soil with Si can improve salt tolerance of barley (*Hordeum vulgare* L.) (Liang, 1999; Liang et al., 1999), maize (*Zea mays* L.) (Shu and Liu, 2001), rice (*Oryza sativa* L.) (Kraska and Breitenbeck, 2010; Yeo et al., 1999), and wheat (*Triticum aestivum* L.) (Ahmad et al., 1992). However, limited research has investigated effects of Si supplement on salt tolerance of turfgrasses. Evaluating the effects of Si supplement on turfgrass salt stress tolerance may further our understanding of the role of Si in alleviating salt stress damage. Therefore, the objective of this study was to investigate effects of Si on turfgrass growth and distribution of K⁺ and Na⁺ in shoots and roots for KBG grown in saline soils.

Materials and Methods

Plant materials and growth conditions. 'Baron' KBG plants were grown at a seeding rate of one pure live seed/cm² in optimum environment in polyvinyl chloride (PVC) pots (20 cm in diameter, 25 cm in height) filled with silt loam soil (USDA system) (fine, montmorillonitic, mesic, Aquic, Arquidoll, pH 7.3), which were collected from Lanzhou University research farm, Lanzhou, China. Nutrient analysis of the soil (at the beginning of the study) indicated the following nutrient levels: 3.4 g·kg⁻¹ total nitrogen, 0.72 g·kg⁻¹ phosphorus, 5.5 g·kg⁻¹ organic matter, 0.353 g·kg⁻¹ soluble sodium (Na), 0.359 g·kg⁻¹ soluble potassium (K), 0.159 g·kg⁻¹ exchangeable and available non-exchangeable Na, 0.013 g·kg⁻¹ exchangeable and available non-exchangeable K, and 4.6 g·kg⁻¹ salt.

The experiment was conducted in four growth chambers set at optimum temperature (23/15 °C, day/night), photosynthetically active radiation of 500 μmol·m⁻²·s⁻¹ with a photoperiod of 14 h, and relative humidity of 70%. Soil water content was maintained at 32.6% (50% of saturated water content) from the date of planting time to the end of the experiment by weighing the PVC and adding tap water back with an electronic balance and to determine the effect of Si without other fertilizer amendment during the whole experimental period (Liu et al., 2009).

Treatments. The experiment consisted of six treatments including a control (no salinity and no Si amendment) and Si amendment at 0, 0.24, 0.48, 0.72, and 0.96 g Si/kg soil levels under salinity stress. Sodium silicate used as a Si source (Na₂SiO₃; Tianjin Double Boat Chemical Co., Tianjin, China) is composed of 102 g·kg⁻¹ Si, 161.8 g·kg⁻¹ Na, and other minor elements such as SO₄²⁻ (1 g·kg⁻¹), Cl⁻ (1 g·kg⁻¹), and lead (0.1 g·kg⁻¹). The sodium silicate was incorporated into each treated pot to obtain the rates of elemental Si. Sodium chloride was added to the pots treated with 0, 0.24, 0.48, or 0.72 g Si/kg soil to equilibrate the amount of Na present in these treatments with the treatment containing 0.96 g Si/kg soil. Thus, the salt content was 10 g·kg⁻¹

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(calculated as NaCl) in all treatments except the untreated control.

Growth analysis. The number of seedlings emerged from each pot was counted every 2 d and the numbers of plants were used to determine the rate of germination. Ten marked plants (randomly selected at earlier beginning of the experiment) from each pot were measured every 4 d for plant height. Plant height was measured from the ground to the top of each plant. Tiller number of each treatment was calculated after 50 d of treatment. Each replicate (pot) was photographed, and the resulting images were processed and analyzed to quantify the percent canopy coverage by using a WinCAM Color Analysis System (Regent Instruments Inc., 2004a, Quebec, Canada). Individual leaf area was calculated using WinFOLIA Scan System (Regent Instruments Inc., 2004a).

Physiological measurements. Cell membrane stability was estimated by measuring electrolyte leakage (EL) of leaves. Samples of 0.5 g of leaves were rinsed with deionized water, immersed in 25 mL of deionized water, and subjected to a vacuum of 48 kPa for 15 min. Leaves were shaken in flasks of deionized water on a shaker for 24 h. The conductivity of the solution (C_{initial}) was measured using a conductivity meter (DDSJ 308A; Shanghai Cany Precision Instrument Co., Ltd., Shanghai, China). Leaves then were killed by autoclaving at 140 °C for 20 min. The conductivity of killed tissues (C_{max}) was measured. Relative percent EL was calculated as using the formula $C_{\text{initial}}/C_{\text{max}} \times 100$ (Liu and Huang, 2000).

Shoots and roots were sampled from each pot, washed at least three times in water, dried in an oven at 80 °C for 3 d, and then ground into powder to pass a 0.5-mm sieve. Shoots and roots were extracted in 10 mL acetic acid (5.7 mL·L⁻¹) for 2 h at 90 °C. Sodium and K were determined in the extract by Cole-Palmer Digital Flame Analyzer, Model 2655-00 (Cole-Palmer Instrument, Chicago, IL) (Flowers et al., 2000).

The experimental design and statistical analysis. There were six treatments with four replications in a completely randomized block design. Each treatment was repeated in four growth chambers as four replications. The main effects of treatments were analyzed by standard analysis of variance procedures using the general linear model (GLM) procedure. Treatment means were separated using the least significant differences option of the GLM procedure test at $P = 0.05$ (SAS Version 9; SAS Institute, Cary, NC).

Results

Germination and growth response. Seed germination rate was significantly reduced by 20% when plants were grown in 0 Si under saline conditions compared with the control at 8 d of treatments (Fig. 1). Germination rate significantly ($P < 0.05$) increased after 12 d of 0.48 g Si treatment compared with that in Si-untreated plants. The germination rate under 0.48 g Si was 28% higher than that of

0 Si under saline conditions after 20 d of treatments. However, application of Si at other rates (0.24, 0.72, 0.96 g) did not affect the germination when compared with 0 Si under saline conditions.

Plant height was greatly reduced in 0 Si under saline conditions compared with the controls after 36 d of treatments (Fig. 2). Supplying 0.72 g Si/kg treatment significantly ($P < 0.05$) increased plant height after 40 d compared with 0 Si under saline conditions. Plant height was 7%, 13%, 34%, and 32% higher than that of 0 Si under saline conditions for 0.24, 0.48, 0.72, and 0.96 g Si treatments, respectively, after 52 d.

Canopy coverage of control plants was significantly increased by 11.7% than plants in 0 Si under saline conditions after 20 d (Fig. 3). There was no significant difference in canopy coverage among all the Si amendment treatments on 32 d of treatment. Coverage was significantly ($P < 0.05$) increased by the use of Si on 44 d. The canopy coverage was 61%, 82%, and 78% higher for 0.48,

0.72, and 0.96 g Si treatments, respectively, compared with 0 Si under saline conditions.

Leaf area and leaf blade length were significantly decreased by 35% and 25%, respectively, in 0 Si under saline conditions compared with the control after 60 d of treatment (Figs. 4 and 5), but no significant differences were detected in maximum leaf width. Supplying plants with 0.48, 0.72, and 0.96 g Si significantly ($P < 0.05$) increased leaf area compared with 0 Si under saline conditions. Leaf area was 33%, 35%, and 33% higher than 0 Si under saline conditions for 0.48, 0.72, and 0.96 g Si treatments, respectively.

Tiller number was significantly decreased $\approx 85\%$ in 0 Si under saline conditions compared with the control after 50 d of treatment (Fig. 6). Tillers per plant under 0.96 g Si was 6.3 times higher than 0 Si under saline conditions. Average tillers per plant were both 3.7 times higher than in 0 Si under saline conditions with Si rates of 0.48 and 0.72 g Si.

Fig. 1. Germination rate of 'Baron' kentucky bluegrass as affected by silicon (Si) amendment at 0, 0.24, 0.48, 0.72, and 0.96 g·kg⁻¹ soil levels under salinity stress and control. Vertical bars on the top indicate least significant difference values ($P \leq 0.05$) for treatments comparison at the given day of treatment.

Fig. 2. Plant height of 'Baron' kentucky bluegrass as affected by silicon (Si) amendment at 0, 0.24, 0.48, 0.72, and 0.96 g·kg⁻¹ soil levels under salinity stress and control. Vertical bars on the top indicate least significant difference values ($P \leq 0.05$) for treatments comparison at the given day of treatment.

Fig. 3. Canopy coverage of 'Baron' kentucky bluegrass as affected by silicon (Si) amendment at 0, 0.24, 0.48, 0.72, and 0.96 g·kg⁻¹ soil levels under salinity stress and control. Vertical bars on the top indicate least significant difference values ($P \leq 0.05$) for treatments comparison at the given day of treatment.

Fig. 4. Leaf area of 'Baron' kentucky bluegrass as affected by silicon (Si) amendment at 0, 0.24, 0.48, 0.72, and 0.96 g·kg⁻¹ soil levels under salinity stress and control after 60 d of treatments. Treatments with same lowercase are not significantly different at $P \leq 0.05$.

Fig. 5. Leaf blade length of 'Baron' kentucky bluegrass as affected by silicon (Si) amendment at 0, 0.24, 0.48, 0.72, and 0.96 g·kg⁻¹ soil levels under salinity stress and control after 60 d of treatments. Treatments with same lowercase are not significantly different at $P \leq 0.05$.

Electrolyte leakage. EL of leaves was $\approx 33\%$ higher in 0 Si under saline conditions compared with that of the control after 60 d of treatment (Fig. 7). EL was significantly ($P < 0.05$) reduced by the use of Si under 0.48

and 0.72 g Si amendment treatments compared with that of 0 Si under saline conditions. After 60 d of treatment, EL was 40%, 57%, 60%, and 43% lower than that of 0 Si under saline conditions for plants receiving

rates of 0.24, 0.48, 0.72, and 0.96 g Si, respectively.

Distribution of Na⁺ and K⁺. Concentrations of K⁺ were higher in shoots than in roots in all treatments after 60 d of treatments (Fig. 8). The concentrations were $\approx 36\%$ and 22% lower in shoots and in roots, respectively, in 0 Si under saline conditions relative to the controls. There was an increase in shoot K⁺ concentrations with the use of Si, but it had no significant changes in roots in all the Si amendment treatments.

The concentrations of Na⁺ were 7.78 and 4.51 times higher in shoots and in roots, respectively, under 0 Si under saline conditions than the control after 60 d treatment (Fig. 9). With Si application, the concentrations of Na⁺ decreased compared with 0 Si under saline conditions. The content of Na⁺ was 13%, 38%, 48%, and 40% lower in shoots than that of 0 Si under saline conditions for 0.24, 0.48, 0.72, and 0.96 g Si amendment treatments, respectively, and that was 24%, 27%, 36%, and 28% lower in roots, respectively.

Na⁺/K⁺ ratios were 11.11 and 8.80 times higher in shoots and in roots, respectively, under 0 Si under saline conditions than the control after 60 d of treatments (Fig. 10). Na⁺/K⁺ ratio also decreased with the addition of Si but changed more in shoots than in roots in all Si amendment treatments. The ratio in roots was higher than in shoots of each salinity treatment.

Discussion

Crops grown in salt-affected soil may lead to reduction in growth and productivity (Netondo et al., 2004). High salt concentrations in soils account for large decreases in yields of a wide variety of crops all over the world (Tester and Davenport, 2003). Compared with other cool-season turfgrass species, KBG exhibited less salt tolerance than perennial ryegrass (*Lolium perenne* L.) and creeping bentgrass (*Agrostis stolonifera* L.) (Jing et al., 2009). Previous studies have shown that KBG plants were killed after 10- to 15-d exposure to 1.5% NaCl treatment (Fei et al., 2005). Turfgrass germination is greatly retarded and seedling survival is difficult under saline conditions (Daniel and Freeborg, 1987). In this study, germination rate decreased in saline soils and plants exhibited 12% to 35% reduction in canopy coverage, tiller number, and plant height relative to the control.

Silicon has been regarded as a beneficial element in a number of species of the Poaceae and Cyperaceae (Jin, 2001). The Si content in dry matter of *Poa alpine* L., *Poa chaixii* Will., and *Poa secunda* J. S. Presl. were 0.61, 0.7 to 0.9, and 2.63%, respectively (Carnelli et al., 2001). Application of Si as sodium metasilicate doubled plant Si concentration and increased grain yield in rice (Winslow, 1992). In experiments with rice and wheat, addition of silicate to the growing solution enhanced the resistance of the plants to salinity stress (Epstein, 1994). The application of Si promoted

Fig. 6. Tiller number of 'Baron' kentucky bluegrass as affected by silicon (Si) amendment at 0, 0.24, 0.48, 0.72, and 0.96 g·kg⁻¹ soil levels under salinity stress and control after 50 d of treatment. Treatments with same lowercase are not significantly different at $P \leq 0.05$.

Fig. 7. Electrolyte leakage (%) of 'Baron' kentucky bluegrass as affected by silicon (Si) amendment at 0, 0.24, 0.48, 0.72, and 0.96 g·kg⁻¹ soil levels under salinity stress and control after 60 d of treatment. Treatments with same lowercase are not significantly different at $P \leq 0.05$.

Fig. 8. K⁺ concentration of 'Baron' kentucky bluegrass as affected by silicon (Si) amendment at 0, 0.24, 0.48, 0.72, and 0.96 g·kg⁻¹ soil levels under salinity stress and control after 60 d of treatment. Treatments with same lowercase in shoots or in roots are not significantly different at $P \leq 0.05$.

germination rate and leaf growth of KBG in saline soils and this is in agreement with the results by Li and Ma (2003). In our experiment, the maximum germination rates of the Si amendment treatments were more than

20% higher than that under 0 Si under saline conditions. Canopy coverage of the Si amendment plants was nearly twice that of 0 Si under saline conditions and the tiller number in Si amendment plants was more than six

times of 0 Si under saline conditions. Similar positive effects of Si have been found on the growth of cucumber plants (Epstein, 1994). The present study also indicated that Si application was able to maintain a lower EL under Si amendment treatment than 0 Si under saline conditions, suggesting that Si may alleviate cellular membrane damage caused by salinity stress of KBG. This may be a result of Si supplement to the absorption of K⁺ and Na⁺ from the soil and transportation in the plant from roots to shoots.

Although K⁺ is a major macronutrient (Wang et al., 2004), the accumulation of K⁺ in the roots and leaves is strongly inhibited by salinity (Netondo et al., 2004). In this study, salinity caused K⁺ reduction by 36% in shoots and 22% in roots. Too great of a reduction in the concentration of K⁺ in leaves under salinity could cause a specific ion deficiency that reduces plant growth (Netondo et al., 2004).

For many plants (such as graminaceous crops), Na⁺ is the primary cause of ion-specific damage (Tester and Davenport, 2003). In this study, salinity caused 7.78 and 4.51 times the Na⁺ concentration rise both in shoots and in roots compared with controls. High concentrations of Na⁺ may have disturbed intracellular ion homeostasis, which led to membrane dysfunction, attenuation of metabolic activity, and secondary effects that cause growth inhibition and ultimately lead to cell death (Wang et al., 2004). The application of 0.72 g Si inhibited 48% Na⁺ in shoots and 36% in roots compared with 0 Si under saline conditions. In experiments with rice and wheat, addition of silicate to the solution cultures also reduced the Na⁺ concentration in the plants (Epstein, 1994). Slowly absorbed Na⁺ can reduce toxicity of Na⁺ accumulation (Yin et al., 1997).

Salinity stress, especially NaCl stress, reduced K⁺ content and K⁺/Na⁺ ratios in shoots and roots but increased Na⁺ content and enhanced the selectivity of K⁺/Na⁺. The increments of Na⁺ contents in shoot were higher than in the roots. NaCl stress duration affected the K⁺ and Na⁺ contents significantly and reduced the transportation selectivity ratios of K⁺ and Na⁺, but NaCl concentration mainly influenced the absorption ratios of K⁺ and Na⁺ (Flowers, 2004). A previous study showed that with the increasing of NaCl concentration, Na⁺ content increased, whereas K⁺ content and ratios of wheat K⁺/Na⁺ declined (Xu et al., 2002). Under salinity stress, a representative index for balanced ions is the decrease of K⁺/Na⁺ ratio (Li et al., 2005; Rasan et al., 2000). The larger the K⁺/Na⁺ ratio, the stronger ability for the root to inhibit Na⁺ and promote transportation of K⁺ to shoots, indicating a stronger selective transport capacity of the root system (Wang, 1996; Wang et al., 1996, 2004). The salt tolerance in grasses is liable to have some certain selectivity to absorb K⁺ and the salt tolerance in various grasses can be identified in various species through comparing the K⁺/Na⁺ ratio of leaf lamina when they are grown on soils that have the same salt contents

Fig. 9. Na⁺ concentration of 'Baron' kentucky bluegrass as affected by silicon (Si) amendment at 0, 0.24, 0.48, 0.72, and 0.96 g·kg⁻¹ soil levels under salinity stress and control after 60 d of treatment. Treatments with same lowercase in shoots or in roots are not significantly different at $P \leq 0.05$.

Fig. 10. Na⁺/K⁺ ratio of 'Baron' kentucky bluegrass as affected by silicon (Si) amendment at 0, 0.24, 0.48, 0.72, and 0.96 g·kg⁻¹ soil levels under salinity stress and control after 60 d of treatment. Treatments with same lowercase in shoots or in roots are not significantly different at $P \leq 0.05$.

(Wang et al., 2002). Grasses having higher K⁺/Na⁺ rate were evaluated to possess also much greater variability in salt tolerance (Weng et al., 1998). High levels of Na⁺, or high Na⁺/K⁺ ratios, can disrupt various enzymatic processes in the cytoplasm. Other nutrient deficiencies can occur because elevated Na⁺ inhibits the uptake of other nutrients directly by interfering with transporters in the root plasma membrane such as K⁺-selective ion channels (Tester and Davenport, 2003).

In summary, germination rate and growth of KBG decreased in saline soils. The application of Si increased seed germination and promoted shoot growth under saline conditions. Under salinity conditions, application of Si induced the transfer of K⁺ from roots to shoots but inhibited the absorption and transfer of Na⁺, which may lead to less damage from salinity to the plants and result in higher turf quality.

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