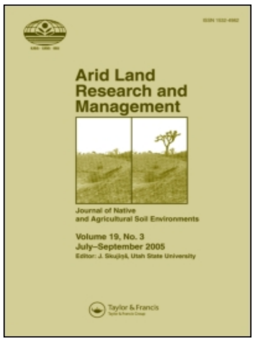

Arid Land Research and Management

ISSN: 1532-4982 (Print) 1532-4990 (Online) Journal homepage: http://www.tandfonline.com/loi/uasr20

Candidate halophytic grasses for addressing land degradation: Shoot responses of Sporobolus airoides and Paspalum vaginatum to weekly increasing NaCl concentration

Mohammad Pessarakli, David D. Breshears, James Walworth, Jason P. Field & Darin J. Law

ARID LAND RESEARCH AND MANAGEMENT
2017, VOL. 31, NO. 2, 169–181
http://dx.doi.org/10.1080/15324982.2017.1284944

Candidate halophytic grasses for addressing land degradation: Shoot responses of *Sporobolus airoides* and *Paspalum vaginatum* to weekly increasing NaCl concentration

Mohammad Pessarakli[a], David D. Breshears[b], James Walworth[c], Jason P. Field[b], and Darin J. Law[b]

[a]School of Plant Sciences, College of Agriculture and Life Sciences, The University of Arizona, Tucson, Arizona, USA; [b]School of Natural Resources and the Environment, College of Agriculture and Life Sciences, The University of Arizona, Tucson, Arizona, USA; [c]Department of Soil, Water and Environmental Sciences, College of Agriculture and Life Sciences, The University of Arizona, Tucson, Arizona, USA

ABSTRACT
In many arid and semiarid regions worldwide, high levels of soil salinity is a key driver of land degradation, as well as a key impediment to re-establishing plant cover. Combating land degradation and erosion associated with soil salinity requires experimental determination of plant species that can grow in soils with high levels of salinity and can be used to re-establish plant cover. Herein, we evaluated the responses of untested candidate cultivars of two halophytic grass species to high soil salinity: alkali sacaton (*Sporobolus airoides* Torr.) and seashore paspalum (*Paspalum vaginatum* Swartz). We evaluated the growth responses of both species in a greenhouse under control (no-salt) and various levels of NaCl salinity (EC 8, 16, 24, 32, 40, and 48 dSm^{-1}) using Hoagland solution in a hydroponics system in a randomized complete block design trial. At all salinity levels, sacaton grass had a greater shoot height, shorter root length, lower shoot fresh and dry weights, and poorer color and general quality compared to seashore paspalum. The shoot fresh and dry weights of both grasses were greatest at the low to medium levels of salinity, with the greatest response observed at EC 16 dSm^{-1}. At the highest level, salinity significantly reduced shoot fresh and dry weights of both grasses. Because growth of both halophytic species exhibited high tolerance to salinity stress and were stimulated under low to medium levels of salinity, both species could be considered suitable candidates for re-establishing plant cover in drylands to combat desertification and land degradation associated with high levels of soil salinity.

ARTICLE HISTORY
Received 25 October 2016
Accepted 17 January 2017

KEYWORDS
Alkali sacaton grass; salt stress; seashore paspalum; true halophyte; wind erosion

Introduction

Soil salinization, as well as water quality and quantity, are major problems worldwide, especially in arid regions and areas with limited water resources (Miyamoto, Glenn, and Olsen 1996; Pessarakli 2011, 2015; Pessarakli and McMillan 2014; Pessarakli, Haghighi, and Sheibanirad 2015). Arguably, one of the most central land management challenges

CONTACT Mohammad Pessarakli pessarak@email.arizona.edu School of Plant Sciences, Forbes Bldg., Room 303, College of Agriculture and Life Sciences, 1140 E. South Campus Drive, P.O. Box 210036, The University of Arizona, Tucson, AZ 85721, USA.
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uasr.

for water-limited systems is maintaining adequate vegetation cover to prevent land degradation and desertification associated with erosion and soil salinization (Schlesinger et al. 1990; Millennium Ecosystem Assessment (MEA) 2005; Hill et al. 2008). This is likely to become more widespread and difficult to manage as many drylands are projected to experience increased aridity within years to decades due to reduced precipitation and hotter temperatures (Seager et al. 2007; Intergovernmental Panel on Climate Change (IPCC) 2012).

The buildup of salts in the rhizosphere of the soil can occur in many ways, including reduced infiltration from soil compaction, irrigation with poor quality water, seawater intrusion, saline parent materials, application of chemical (commercial) fertilizers, evapotranspiration exceeding precipitation, and high temperatures causing high evapotranspiration. Reducing salt concentration in the rhizosphere can be especially challenging in arid regions where water resources are limited, often making reclamation methods such as leaching salts with supplemental water impractical or infeasible. Soil salinization is also greatly influenced by the amount and distribution of plant cover at the soil surface, as well as by human activities such as agricultural practices, livestock grazing, reservoir construction, groundwater pumping, and management-induced salinization (Young et al. 2015).

To maintain perennial vegetation coverage, particularly in water-limited systems, plant/crop growers and agricultural managers must deal with reduced growth, tissue dehydration, nutritional imbalances, and specific ion toxicities, slow recovery from injury, and poor long-term persistence that can be caused by salinity (Romero-Aranda et al. 1998; Katerji et al. 2000). High levels of soil salinity can lead to a reduction in plant cover and a decrease in both the aboveground and belowground biomass leaving these systems highly susceptible to wind and water erosion (Okin, Gillette, and Herrick 2006; Breshears et al. 2009; Field, Breshears, and Whicker 2009) and to further land degradation following the loss of stabilizing soil-plant feedbacks (e.g., plant cover reduces erosion and increases infiltration, which in turn increases the amount of plant available water in the rhizosphere, encouraging further plant growth to help stabilize the site).

An effective strategy to enhance plant survival and recovery from salt stress is to use cultivars with superior salinity tolerance (Ashraf 1994; Flowers and Yeo 1995; Glenn, Brown, and Blumwald 1999; Munns et al. 2002). However, development of salt-tolerant cultivars is not simple because the trait is quantitative, controlled by many physiological mechanisms and genes (Holmberg and Bulow 1998; Grover, Sahi, and Sanan 1999; Cushman and Bohnert 2000). Additionally, there is a lack of standardized screening protocols at both intra- and inter-species levels (Isla, Aragues, and Royo 1998). Therefore, reliable selection criteria are fundamental for developing salt-tolerant cultivars.

Perennial vegetation coverage in water-limited regions must maintain adequate growth and persistence under variable levels of soil salinity or salinity-laden water over several years to be reproductively successful. Accurate assessment of salinity tolerance of perennial, halophytic plants, therefore, should be based on growth at non-saline, intermediate, and high salinity levels. In addition to shoot evaluation, verdure and root parameters should be measured in tolerance trials, especially for plant species exposed to combined biotic or abiotic stresses (Munns and Termaat 1986; Lee, Carrow, and Duncan 2004; Lee, Duncan, and Carrow 2004). Therefore, halophytic plant species such as bermudagrass (*Cynodon dactylon* L.), seashore paspalum (*Paspalum vaginatum* Swartz), and saltgrass (*Distichlis spicata* L., Greene) need to be evaluated at salinity regimes up to seawater level

Table 1. Summary of the responses of our previously tested various halophytic plant species to salinity stress.

Plant/Grass species	Salt tolerance levels	References
Bermudagrass (*Cynodon dactylon* L.)	Plant growth was stimulated at low salinity levels (EC up to 8 dSm^{-1}, 5,100 mgl^{-1}), no significant differences were found between the control and the moderate salinity levels (EC 8 to 20 dSm^{-1}, @ 5,100-13,000 mgl^{-1}), but growth was reduced at higher salinity levels (EC $>$ 20 dSm^{-1}, $>$13,000 mgl^{-1}), and growth was ceased at EC $>$ 50 dSm^{-1}, $>$32,000 mgl^{-1}).	Marcum and Pessarakli (2006), Pessarakli (2015), Pessarakli and Kopec (2008), Pessarakli and Touchane (2011)
Saltgrass (*Distichlis spicata* L.)	Plant growth was stimulated at low salinity levels (EC up to 12 dSm^{-1}, @ 7,700 mgl^{-1}), no significant differences were found between the control and the moderate salinity levels (EC 12 to 30 dSm^{-1}, @ 7,700–19,200 mgl^{-1}), but growth was reduced at higher salinity levels (EC $>$ 30 dSm^{-1}, $>$19,200 mgl^{-1}), and growth was ceased at EC $>$ 65 dSm^{-1}, $>$42,000 mgl^{-1}).	Marcum, Pessarakli, and Kopec (2005), Pessarakli (2011, 2016), Pessarakli and Kopec (2005, 2008), Pessarakli, Marcum, and Kopec (2005), Pessarakli, Kopec, and Ray (2011)
Seashore paspalum (*Paspalum vaginatum* Swartz)	Plant growth was stimulated at low salinity levels (EC up to 10 dSm^{-1}, @ 6,400 mgl^{-1}), no significant differences were found between the control and the moderate salinity levels (EC 10 to 25 dSm^{-1}, @ 6,400–16,000 mgl^{-1}), but growth was reduced at higher salinity levels (EC $>$ 25 dSm^{-1}, $>$16,000 mgl^{-1}), and growth was ceased at EC $>$ 55 dSm^{-1}, $>$35,200 mgl^{-1}).	Pessarakli and Kopec (2008), Pessarakli and McMillan (2014), Pessarakli and Touchane (2011)

to select the best genotype (see related studies summarized in Table 1). Revegetation of saline soils using plant species that are better adapted to the harsh and stressful conditions of the environments is likely the most effective practice owing to its affordability and feasibility for widespread implementation.

Re-establishing and maintaining vegetation cover is a critical factor in addressing desertification (Millennium Ecosystem Assessment (MEA) 2005; D'Odorico et al. 2013) and associated soil erosion problems. Bare areas are much more vulnerable to soil erosion by both wind and water compared to areas where vegetation cover is intermediate to dense (Li et al. 2007; Breshears et al. 2009). Vegetation cover not only prevents erosional processes, but also improves soil by capturing nutrients in aeolian and fluvial sediments (Ludwig et al. 2005; Field et al. 2012; Field et al. 2015). Plants provide numerous other feedbacks to soils that improve soil quality, including moisture regulation, microclimate control, and biogeochemical exchange. Halophytes are particularly effective in this regard by reducing salinity level of the soil via removing the salts or by utilizing saline and low quality waters for their growth. Bermudagrass (*Cynodon dactylon* L.), seashore paspalum (*Paspalum vaginatum* Swartz), sacaton grass (*Sporobolus airoides* Torr.), and saltgrass (*Distichlis spicata* L., Greene), true halophytes, are among the most effective halophytic plant species to be established under arid regions with highly saline soils, limited water, and drought condition. These plant species have multiple usages including: animal feed, soil conservation and reclamation, and use for lawns, recreation areas, and especially xeriscape landscaping. They have great potential to maintain growth and combat desertification processes.

Although some cultivars of some halophytic grass species have been evaluated for salinity tolerance levels (Table 1), a wider range of tested cultivars are needed to increase management options. Based on work to date (Table 1), we identified an additional cultivar of two halophytic grass species as candidates.

The objectives of this study were to evaluate establishment and growth responses of two halophytic plant species, seashore paspalum (*Paspalum vaginatum* Swartz), cv. sea spray and alkali sacaton grass (*Sporobolus airoides* Torr.) as candidate grass species for use in potential restoration of degraded drylands with high soil salinity. More specifically, we evaluated shoot and root length, shoot fresh and dry weight, and general grass quality under desert conditions. We also compared responses of these two species to identify the one likely to be more effective for establishment and survival under saline desert soils and for combating desertification.

Methods

Alkali sacaton grass (*Sporobolus airoides* Torr.) and seashore paspalum (*Paspalum vaginatum* Swartz), cv. sea spray were studied to evaluate their growth responses to salinity. The grasses were studied in a greenhouse at the University of Arizona to evaluate their growth responses under control (no-salt) and various levels of NaCl salinity (EC 8, 16, 24, 32, 40, and 48 dSm^{-1}), using Hoagland nutrient solution in a hydroponics system. Four replications of each treatment were used in a randomized complete block design trial. The grasses were grown either from seed (alkali sacaton) (Great Basin Seed, Ephram, Utah, USA) or by vegetative propagules (seashore paspalum) (Simplot/Jaklin Seed, Post Falls, Idaho, USA) in cups measuring 9 cm diameter and 7 cm height. The experiment was conducted in a greenhouse at the University of Arizona started on October 25, 2015 (planting the seeds for the establishment phase of the study) continued during the Spring and Summer of 2016 (the salinity stress phase of the study) and ended in August 12, 2016.

Four replicates of each grass species and each treatment were used in this investigation. The plants were allowed to grow under normal (non-saline) condition for 90 days from germination (establishment period). The greenhouse plant growth condition was as follows, 35°C (95°F) day temperature 25°C (77°F) night temperature 14-hour day length (photoperiod), and 50% relative humidity. During this period, the plant shoots were harvested weekly to develop uniform and equal-size plants. The harvested plant materials were discarded. Before the initiation of the salinity phase of the experiment, the roots were cut to 2.5 cm in length to have plants with uniform roots and shoots for the stress phase of the experiment. The culture solutions were changed biweekly to ensure adequate levels of essential plant nutrient elements for normal growth and development.

The salt treatments were initiated by adding NaCl to the culture solutions for the various (EC 8, 16, 24, 32, 40, and 48 dSm^{-1}) salinity treatments. The procedure was ramp up (this is a common practice for salt stress studies), the culture solutions were salinized (EC was raised to 8 dSm^{-1} each week). The grasses were grown at EC 8 dSm^{-1} for 1 week, then the shoots were harvested at the 2.5 cm height for the fresh and dry matter weight determination. Salinity levels of the culture solution were raised to EC 16 dSm^{-1} for the second week after which the same measurements were made. The Salinity levels of the culture solutions were raised in the same manner to reach the EC 24, 32, 40, and 48 dSm^{-1} for the subsequent 3rd, 4th, 5th, and 6th week of growth and data collections, respectively. The culture solution levels in the tubs were marked at the 15-liter volume and maintained at this level. As previously mentioned, grasses were grown at each of the salinity levels for 1 week, then grass shoots were harvested for evaluation of the fresh and dry matter (DM) production. At each weekly harvest for all salinity levels, both shoot and root lengths were determined. The harvested shoots were oven-dried at 70°C for 48 hours and DM weights were measured and recorded, as an estimate of the weekly plant DM production. Shoot succulence was calculated by dividing shoot fresh weight by shoot dry weight after each weekly harvest (each salinity level). Before each harvest, grass color and general quality were evaluated according to the NTEP (National Turfgrass Evaluation Program) scoring procedures using scales of 1–10 where 1 represents the lightest green and the lowest quality and 10 represents the darkest green and highest quality. According to NTEP, a score of 6 or higher is considered acceptable color and quality (NTEP, National Turf Evaluation Program, established known Rules and Regulations, http://www.ntep.org/reports/ratings.htm). At the termination of the experiment, the last harvest, plant roots as well as shoots were harvested, oven dried at 70°C, and DM weights were determined and recorded.

The data were subjected to Analysis of Variance (ANOVA) using SAS statistical package (SAS Institute, Inc. 1991). The treatment means were separated with the Duncan Multiple Range Comparison test.

Results

Both sacaton grass and seashore paspalum grew at the different levels of salinity (EC 8, 16, 24, 32, 40, and 48 dSm^{-1}), but responded differently. Notably, differences in shoot and root lengths, shoot fresh and dry weights, shoot succulence, and color and general quality were detected (Figure 1).

Shoot height and root length

Relative to the non-saline control, shoot height of both sacaton grass and seashore paspalum were stimulated at salinity levels EC 8–40 dSm^{-1}, but not at the highest salinity level, EC 48 dSm^{-1} (Figure 2). Seashore paspalum shoot height was elevated relative to the control in the presence of EC 16 and 24 dSm^{-1} of salinity. For both grasses, the tallest shoot heights were found at the low to medium salinity levels between EC 8 and 40 dSm^{-1} (Figure 2, see also Figure 1: EC 8, 16, and 24 dSm^{-1}). At all salinity levels, including the control, shoot height of sacaton grass was substantially higher than that of seashore paspalum (Figure 1). In contrast to the shoot height, the root length of seashore paspalum was significantly longer than that of sacaton grass at all, but the lowest salinity level, EC 8 dSm^{-1} (Figure 2). For both grass species, compared to the shoot height, the root length was less affected by NaCl salinity (Figure 2).

Shoot fresh weight, shoot dry matter (DM) weight, and shoot succulence

The shoot biomass of seashore paspalum was enhanced at the medium levels of salinity with the highest enhancement observed at the EC 16 dSm^{-1} (Figure 3). At the highest salinity level (EC 48 dSm^{-1}), the shoot fresh weight of seashore paspalum was depressed relative to the other treatments (Figure 3). At each salinity level, the shoot fresh weight of seashore paspalum was significantly higher than that of sacaton grass (Figure 3). Reduction in biomass production due to the highest level of salinity stress (EC 48 dSm^{-1}) was more pronounced than the reduction in shoot heights in both sacaton grass and seashore paspalum.

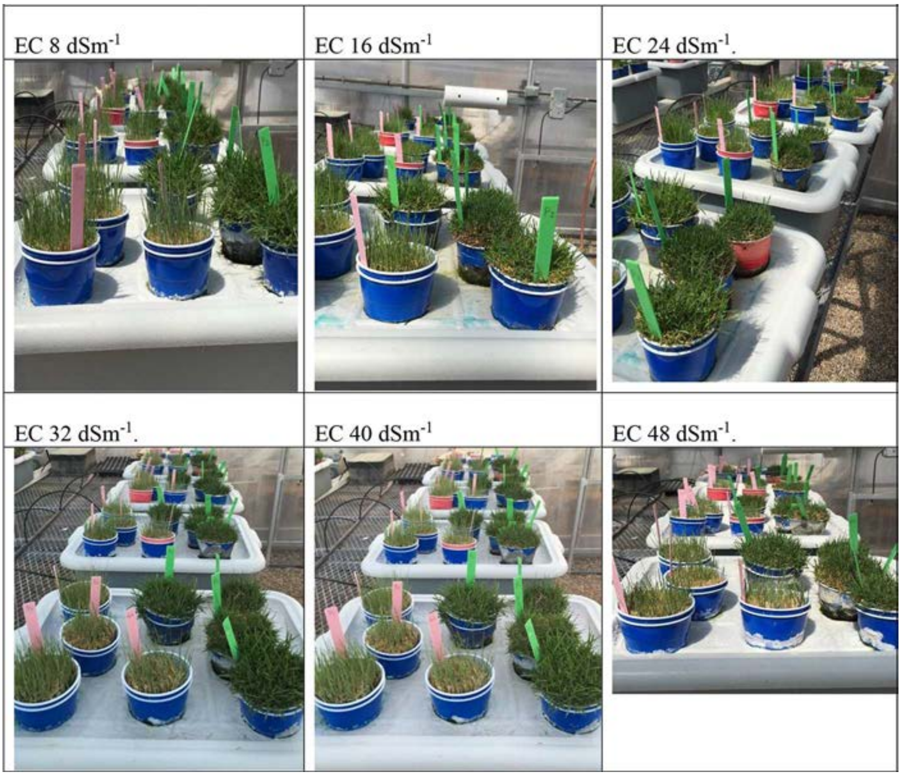

Figure 1. Seashore paspalum (green stickers, "P") and Alkali sacaton grass (pink stickers, "S") under various levels of NaCl salinity.

The shoot DM weight response of seashore paspalum followed a similar pattern as the shoot fresh weight and was enhanced at the EC levels of 16 to 40 dSm^{-1}, whereas DM of sacaton grass was unaffected by salinity stress (Figure 3). Similar to the shoot fresh weights of the grasses, shoot DM weight of sacaton grass was more severely affected by NaCl salinity than that of seashore paspalum DM weight (Figure 3).

Shoot succulence of seashore paspalum increased at all but the highest level of NaCl (EC 48 dSm^{-1}). Contrastingly, shoot succulence of sacaton grass only responded to the EC 48 $dS{\cdot}m^{-1}$; it was significantly lower compared to the non-saline control (Figure 3).

Root fresh and dry matter (DM) weights

Cumulative root fresh and DM weights of seashore paspalum (9.25 and 0.70 g, respectively) were significantly higher than those of sacaton grass (3.02 and 0.29 g, respectively). Several of our previous studies showed that seashore paspalum had a much more vigorous growth compared to many other grasses (i.e., saltgrass and bermudagrass). The greater biomass of shoots and roots of seashore paspalum compared to sacaton grass in the present study (Figures 2 and 3) may have been due to the more vigorous and higher growth rate of seashore paspalum under the control or any salinity treatment. In short, the genotypic growth difference played the dominant role in determining biomass production of these grasses

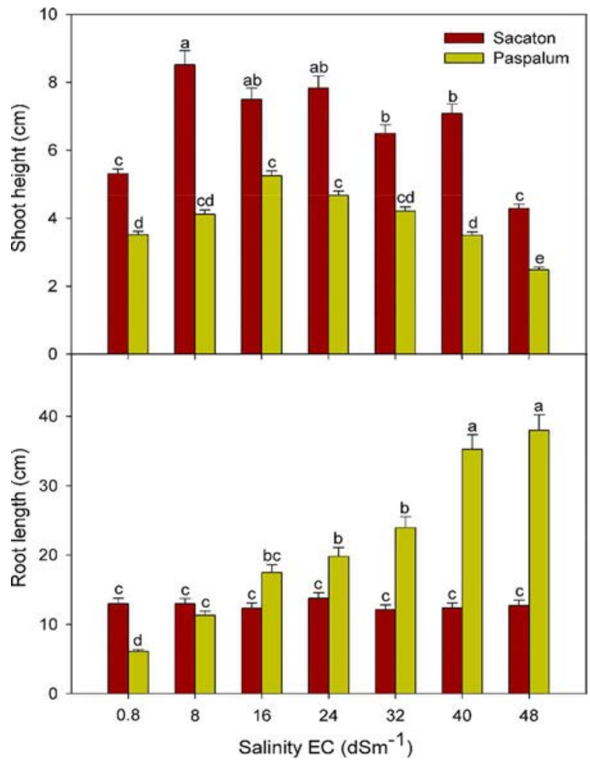

Figure 2. Alkali sacaton grass and Seashore paspalum shoot and root lengths under various levels of NaCl salinity. The data are related to weekly shoot and root lengths per individual growing cup.

grown with or without salinity stress as clearly shown in plant succulence (the ratios of the shoot fresh weights to dry weights) of both species (Figure 3).

Colors and general qualities

Grass color and general quality, evaluated weekly (Figure 1), indicate that for all treatments and at all salinity levels, both color and general quality of seashore paspalum were significantly better than that of sacaton grass (Figure 4). For sacaton grass, the color and the general quality were acceptable only up to EC 24 dSm^{-1}. As stated earlier in the Methods, according to NTEP, a score of 6 (threshold value) or higher (the scale is 1-10) is considered acceptable color and quality (NTEP, National Turf Evaluation Program, established known Rules and Regulations, http://www.ntep.org/reports/ratings.htm). An acceptable score for the grass in any environment, including desert regions is an indication of a healthy grass and can be grown satisfactorily under such environmental condition. However, the color and the general quality of seashore paspalum were greater than 6 for all the salinity treatments (Figures 1 and 4), indicating greater salinity tolerance for seashore paspalum than for sacaton grass.

Recovery

After the termination of the experiment, the grasses were transferred to water (no-salt) for a week, then transferred to half-strength Hoagland solution. All the grasses completely

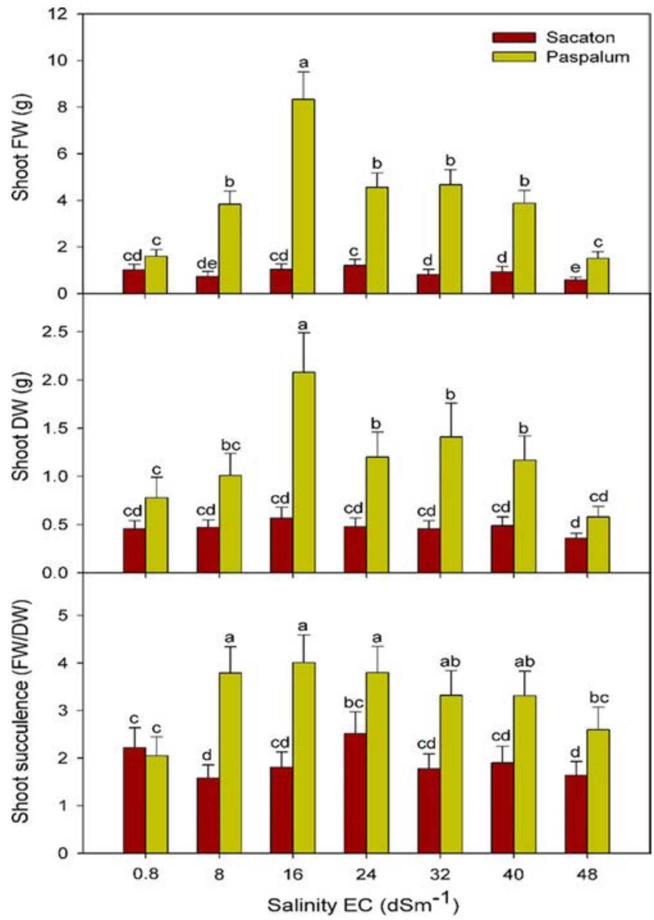

Figure 3. Alkali sacaton grass and Seashore paspalum shoot fresh and dry weights and shoot succulence under various levels of NaCl salinity. The data are related to weekly shoot clippings and not clipped roots per individual growing cup.

recovered and showed normal growth, as illustrated for grasses grown for 1 week in water and then 4 weeks in half-strength Hoagland solution (Figure 5).

Discussion

Our results showed for all the studied parameters, especially for seashore paspalum, low levels of salinity stimulated growth and the moderate levels of salinity did not have adverse effects on our measured parameters. This indicates that both the cultivars of these grass species are true-halophytes. Only at the highest salinity level (EC 48 dSm^{-1}) were shoot fresh and dry weights of seashore paspalum significantly reduced. These results are corroborated by that of Pessarakli, Marcum, and Kopec (2005) who found that shoot succulence of saltgrass (*Distichlis spicata*), cv. WA12 (another halophytic plant species) increased as the salinity levels of the culture solutions increased up to 200 mM NaCl (EC 18.3 dSm^{-1}). The reduction in biomass production at the highest salinity level (EC 48 dSm^{-1}) was more pronounced than in reduction in shoot heights in both sacaton grass and seashore paspalum. The decrease in plant biomass production due to the highest level

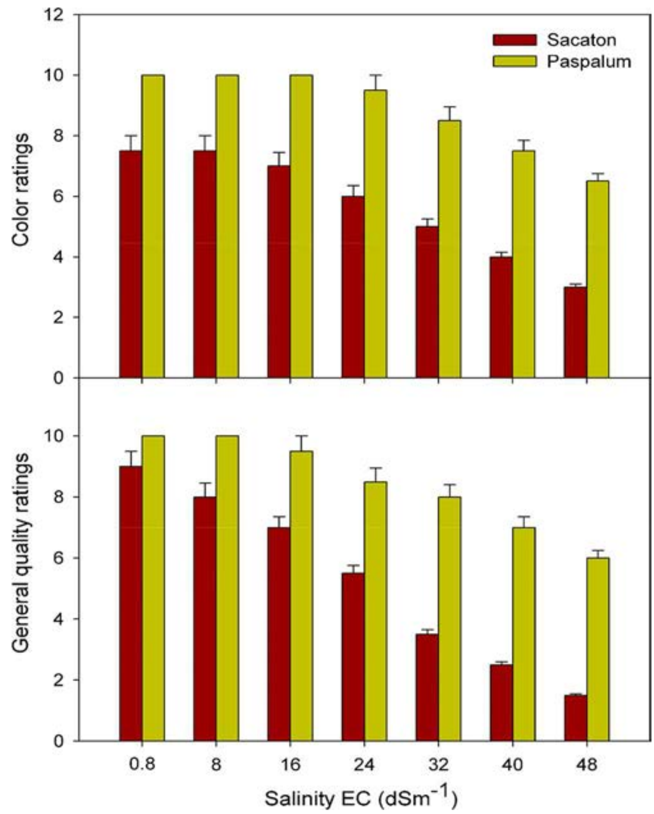

Figure 4. Alkali sacaton grass and Seashore paspalum general qualities and color under various levels of NaCl salinity. The data are related to weekly evaluations of the general qualities and color of the grasses per individual growing cup.

Figure 5. Plants 5 weeks after recovery, growing in water (1 week) and half-strength Hoagland culture solution (4 weeks). Front Row, all the plants in all 4 tubs were transferred from the highest salinity level EC 48 dSm^{-1} to control (no-salt). Seashore paspalum (green stickers, "P") and Alkali sacaton grass (pink stickers, "S").

of salinity may be attributed to low culture solution water potential, specific ion toxicity, or ion imbalance as reported by Greenway and Munns (1980). For both grass species, compared to the shoot height, the root length was less affected by the NaCl salinity stress. This is in agreement with related studies (Sagi et al. 1997; Pessarakli and Touchane 2011), as well as with plant physiology expectations that under stress conditions (salinity, drought stress or lower levels of water and nutrients in the rhizosphere), roots grow more in search of water and/or nutrients.

Projected increases in drought frequency and severity for many arid and semiarid regions worldwide (Intergovernmental Panel on Climate Change (IPCC) 2012) will likely increase the spatial extent and rates of soil salinization in these areas by drying out surface soil more rapidly and reducing the amount of protective vegetation cover, both of which could further amplify soil salinity-erosional feedbacks and the desertification process. Soil salinization processes could be further amplified in these regions due to projected increases in land use and resource exploration that are likely to occur in the near future with increasing demand for ecosystem services (Millennium Ecosystem Assessment (MEA) 2005). Because soil salinization and associated land degradation depend on land use and climate, our results highlight the need for careful land management strategies, especially under projected hotter and drier conditions, to avoid further amplification of soil salinity-erosional feedbacks. Our results also have implications for nutrient cycling and water redistribution in drylands (alkaline sacaton grass patches have been seen in many drylands, but seashore paspalum needs to be tested), particularly at small spatial scales, where the capture of overland flow and sediment by individual plants and vegetation patches have important stabilizing feedbacks that can reduce rates of soil erosion and -associated land degradation (Schlesinger et al. 1990; Ravi et al. 2010). Reducing the amplifying feedbacks between erosion and vegetation requires identification of such cultivars (Ravi et al. 2011).

Conclusions

Since the growth parameters (shoot and root lengths and weights) of both grasses, particularly seashore paspalum, were affected only under the highest level of NaCl salinity (EC 48 dSm^{-1}) and they were stimulated under lower and medium levels of salinity, it can be concluded that these halophytic plant species may be suitable candidates for growth and production in arid regions and water-limited systems to effectively combat desertification and to prevent wind and water erosion in these regions. The risks of current and potential soil salinization in arid regions and water-limited systems are pervasive globally and require valid management options that are economically feasible if these risks are to be combated effectively. Our results add to the existing toolbox of cultivars of halophytic grass species that can be considered as candidates for helping to address desertification and land degradation in areas with high levels of soil salinity.

Acknowledgments

This study was supported by a grant entitled “Research Innovative Challenges (RIC)” awarded by the College of Agriculture & Life Sciences (CALS), and additional partial support from UNAM; hired student at greenhouse, Arizona Agriculture Experiment Station.

References

Ashraf, M. 1994. Breeding for salinity tolerance in plants. *Critical Review of Plant Sciences* 13:17–42. doi:10.1080/713608051

Breshears, D. D., J. J. Whicker, C. B. Zou, J. P. Field, and C. D. Allen. 2009. A conceptual framework for dryland aeolian sediment transport along the grassland–forest continuum: Effects of woody plant canopy cover and disturbance. *Geomorphology* 105:28–38. doi:10.1016/j.geomorph.2007.12.018

Cushman, J. C., and H. J. Bohnert. 2000. Genomic approaches to plant stress tolerance. *Current Opinion in Plant Biology* 3:117–24. doi:10.1016/s1369-5266(99)00052-7

D'Odorico, P., A. Bhattachan, K. F. Davis, S. Ravi, and C. W. Runyan. 2013. Global desertification: Drivers and feedbacks. *Advances in Water Resources* 51:326–44. doi:10.1016/j.advwatres.2012.01.013

Field, J. P., D. D. Breshears, D. J. Law, J. C. Villegas, L. López-Hoffman, P. D. Brooks, J. Chorover, G. A. Barron-Gafford, R. E. Gallery, M. E. Litvak, and R. A. Lybrand. 2015. Critical zone services: Expanding context, constraints, and currency beyond ecosystem services. *Vadose Zone Journal* 14:1–7. doi:10.2136/vzj2014.10.0142

Field, J. P., D. D. Breshears, and J. J. Whicker. 2009. Toward a more holistic perspective of soil erosion: Why Aeolian research needs to explicitly consider fluvial processes and interactions. *Aeolian Research* 1:9–17. doi:10.1016/j.aeolia.2009.04.002

Field, J. P., D. D. Breshears, J. J. Whicker, and C. B. Zou. 2012. Sediment capture by vegetation patches: Implications for desertification and increased resource redistribution. *Journal of Geophysical Research: Biogeosciences* 117:1–9. doi:10.1029/2011jg001663

Flowers, T., and A. Yeo. 1995. Breeding for salinity resistance in crop plants: Where next? *Australian Journal of Plant Physiology* 22:875–84. doi:10.1071/pp9950875

Glenn, E. P., J. J. Brown, and E. Blumwald. 1999. Salt tolerance and crop potential of halophytes. *Critical Review of Plant Science* 18:227–55. doi:10.1016/s0735-2689(99)00388-3

Greenway, H., and R. Munns. 1980. Mechanisms of salt tolerance in non-halophytes. *Annual Review of Plant Physiology* 31:149–90.

Grover, A., C. Sahi, and N. Sanan. 1999. Taming abiotic stresses in plants through genetic engineering: Current strategies and perspective. *Plant Science* 143:101–11. doi:10.1016/s0168-9452(99)00025-4

Hill, J., M. Stellmes, T. Udelhoven, A. Röder, and S. Sommer. 2008. Mediterranean desertification and land degradation: Mapping related land use change syndromes based on satellite observations. *Global and Planetary Change* 64:146–57.

Holmberg, N., and L. Bulow. 1998. Improving stress tolerance in plants by gene transfer. *Trends in Plant Science* 3:61–66. doi:10.1016/s1360-1385(97)01163-1

Intergovernmental Panel on Climate Change (IPCC). 2012. *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the intergovernmental panel on climate change*, ed. C. B. Field. Cambridge, UK, Cambridge University Press. 594p.

Isla, R., R. Aragues, and A. Royo. 1998. Validity of various physiological traits as screening criteria for salt tolerance in barley. *Field Crops Research* 58:97–107. doi:10.1016/s0378-4290(98)00088-4

Katerji, N., J. W. van Hoorn, A. Hamdy, and M. Mastrorilli. 2000. Salt tolerance classification of crops according to soil salinity and to water stress day index. *Agricultural Water Management* 43:99–109. doi:10.1016/s0378-3774(99)00048-7

Lee, G. J., R. N. Carrow, and R. R. Duncan. 2004. Salinity tolerance of selected seashore paspalums and bermudagrasses: Root and verdure responses and criteria. *HortScience* 39:1136–42.

Lee, G. J., R. R. Duncan, and R. N. Carrow. 2004. Salinity tolerance of seashore paspalum ecotypes: Shoot growth responses and criteria. *HortScience* 39:1143–47.

Li, J., G. S. Okin, L. Alvarez, and H. Epstein. 2007. Quantitative effects of vegetation cover on wind erosion and soil nutrient loss in a desert grassland of southern New Mexico, USA. *Biogeochemistry* 85:317–32. doi:10.1007/s10533-007-9142-y

Ludwig, J. A., B. P. Wilcox, D. D. Breshears, D. J. Tongway, and A. C. Imeson. 2005. Vegetation patches and runoff–erosion as interacting ecohydrological processes in semiarid landscapes. *Ecology* 86:288–97. doi:10.1890/03-0569

Marcum, K. B., and M. Pessarakli. 2006. Salinity tolerance and salt gland excretion activity of bermudagrass turf cultivars. *Crop Science* 46:2571–74.
Marcum, K. B., M. Pessarakli, and D. M. Kopec. 2005. Relative salinity tolerance of 21 turf-type desert saltgrasses compared to bermudagrass. *HortScience* 40(3):827–29.
Millennium Ecosystem Assessment (MEA). 2005. *Ecosystems and human well-being: Synthesis*. Vol 1, chapter 5. Washington, DC: Island Press.
Miyamoto, S., E. P. Glenn, and M. W. Olsen. 1996. Growth, water use, and salt uptake of four halophytes irrigated with highly saline water. *Journal of Arid Environment* 32:141–59.
Munns, R., S. Husain, A. R. James, A. G. Condon, M. P. Lindsay, E. S. Lagudah, D. P. Schachtman, and R. A. Hare. 2002. Increasing salt tolerance in crops, and the role of physiologically-based selection traits, Avenues for Assessment and Management. Ann Arbor Press, Chelsea, MI. *Plant and Soil* 247:93–105.
Munns, R., and A. Termaat. 1986. Whole-plant responses to salinity. *Australian Journal of Plant Physiology* 13:143–60. doi:10.1071/pp9860143
Okin, G. S., D. A. Gillette, and J. E. Herrick. 2006. Multi-scale controls on and consequences of Aeolian processes in landscape change in arid and semi-arid environments. *Journal of Arid Environments* 65:253–75. doi:10.1016/j.jaridenv.2005.06.029
Pessarakli, M. 2011. Saltgrass, a high salt and drought tolerant species for sustainable agriculture in desert regions. *International Journal of Water Resources and Arid Environments* 1:55–64.
Pessarakli, M. 2015. Using Bermudagrass (*Cynodon dactylon* L.) in urban desert landscaping and as a forage crop for sustainable agriculture in arid regions and combating desertification. *International Journal of Water Resources and Arid Environments* 4:08–14.
Pessarakli, M. 2016. Saltgrass, a minimum water and nutrient requirement halophytic plant species for sustainable agriculture in desert regions. *Journal of Earth, Environment and Health Sciences* 2:21–27. doi:10.4103/2423-7752.181803
Pessarakli, M., M. Haghighi, and A. Sheibanirad. 2015. Plant responses under environmental stress conditions. *Advances in Plants & Agriculture Research Journal* 2:00073. doi:10.15406/apar.2015.02.00073
Pessarakli, M., and D. M. Kopec. 2005. Responses of twelve inland saltgrass accessions to salt stress. *USGA Turfgrass and Environmental Research Online* 4:1–5.
Pessarakli, M., and D. M. Kopec. 2008. Establishment of three warm-season grasses under salinity stress. *Acta Horticulturae* 783:29–37. doi:10.17660/actahortic.2008.783.2
Pessarakli, M., D. M. Kopec, and D. T. Ray. 2011. Growth responses of various saltgrass (*Distichlis spicata*) clones under salt stress conditions. *Journal of Food, Agriculture, and Environment* 9:660–64.
Pessarakli, M., K. B. Marcum, and D. M. Kopec. 2005. Growth responses and nitrogen-15 absorption of desert saltgrass (*Distichlis spicata*) to salinity stress. *Journal of Plant Nutrition* 28:1441–52. doi:10.1081/pln-200067516
Pessarakli, M., and D. E. McMillan. 2014. Seashore paspalum, a high salinity stress tolerant halophytic plant species for sustainable agriculture in desert regions and combating desertification. *International Journal of Water Resources and Arid Environments* 3:35–42.
Pessarakli, M., and H. Touchane. 2011. Biological technique in combating desertification processes using a true halophytic plant. *International Journal of Water Resources and Arid Environments* 1:360–65.
Ravi, S., D. D. Breshears, T. E. Huxman, and P. D'Odorico. 2010. Land degradation in drylands: Interactions among hydrologic–aeolian erosion and vegetation dynamics. *Geomorphology* 116:236–45. doi:10.1016/j.geomorph.2009.11.023
Ravi, S., P. D'Odorico, D. D. Breshears, J. P. Field, A. S. Goudie, T. E. Huxman, J. Li, G. S. Okin, R. J. Swap, A. D. Thomas, and S. Van Pelt. 2011. Aeolian processes and the biosphere. *Reviews of Geophysics* 49:1–45.
Romero-Aranda, R., J. L. Moya, F. R. Tadeo, F. Legaz, E. Primo-Millo, and M. Talon. 1998. Physiological and anatomical disturbances induced by chloride salts in sensitive and tolerant citrus: Beneficial and detrimental effects of cations. *Plant Cell and Environment* 21:1243–53. doi:10.1046/j.1365-3040.1998.00349.x

Sagi, M., N. A. Savidov, N. P. L'vov, and S. H. Lips. 1997. Nitrate reductase and molybdenum cofactor in annual ryegrass as affected by salinity and nitrogen source. *Physiologia Plantum* 99:546–53. doi:10.1034/j.1399-3054.1997.990405.x

SAS Institute Inc. 1991. *SAS/STAT user's guide*. Cary, NC: SAS Institute Inc.

Schlesinger, W. H., J. F. Reynolds, G. L. Cunningham, L. F. Huenneke, W. M. Jarrell, R. A. Virginia, and W. G. Whitford. 1990. Biological feedbacks in global desertification. *Science* 247:1043–48. doi:10.1126/science.247.4946.1043

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. P. Huang, N. Harnik, A. Leetmaa, N. C. Lau, and C. Li. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316:1181–84.

Young, J., T. K. Udeigwe, D. C. Weindorf, T. Kandakji, P. Gautam, and M. A. Mahmoud. 2015. Evaluating management-induced soil salinization in golf courses in semi-arid landscapes. *Solid Earth* 6:393–402. doi:10.5194/se-6-393-2015