Macrophysiological Responses of Two Forage *Opuntia* Species to Salt Stress♦

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ABSTRACT

The purpose of this study was to evaluate the salt tolerance of two *Opuntia* forage species, *O. spinulifera* Salm-Dyck f. *nacuniana* Le Houér., f. *nov*. and *O. robusta* Wendl., when they were irrigated with saline water with high content of sodium chloride. Soils in pots, under outdoor conditions, were maintained saline by watering them with salt solutions of different concentrations, e.g., 1/8 strength Hoagland's solution in tap water (control), and solutions of NaCl made in 1/8 Hoagland's, whose concentrations were of the order of 25, 50, and 100 mmol. When potted soils acquired approximately the same saline concentration of each solution, one cladode per plot was planted. Pots were randomly arranged in four treatments with four replications of four pots each. Irrigation of cladodes was done with the corresponding saline solution or, eventually, with tap water. After a growth period of 7 months, response to salinity was evaluated by the number of cladodes produced, their dry weight, and the root dry weight. Results showed that above-growth yield was not affected significantly until treatment of 50 mmol NaCl inclusive, but at 100 mmol NaCl (considered as high saline solution) yield was depressed in the following values: 33 and 20% for number of cladodes produced, 55 and 55% for cladode dry biomass, and 70 and 61% for root dry biomass for *O. robusta* and *O. spinulifera*, respectively. Under the conditions of this assay, both *Opuntia* species may be considered as medium tolerant to salt stress. *O. spinulifera* may be considered as less tolerant to soil salinity than *O. robusta* because the root yield was reduced with respect to the control by 20% at only 25 mmol NaCl concentration. In spite of that, both species would be suitable for eco-cultivation in dry ecosystems using for irrigation the currently low quality water from the water table, provided that certain agronomic principles are observed.

Keywords: *Opuntia* spp.; tolerance to salinity; saline water irrigation; eco-cultivation in saline areas

INTRODUCTION

Arid regions offer optimal light and temperature conditions for establishing plants for revegetation purposes, but the water deficit causes extensive reliance on irrigation. In some areas of arid ecosystems, water for irrigation may be obtained from the water-table. Notwithstanding, ground water in dry environments usually contains an important amount of dissolved salts which, by evaporation, becomes more and more concentrated in the soil affecting adversely the growth and development of most plants. On the other hand, saline soils frequently occur in arid and semiarid regions which should be utilized by introducing plants tolerant to salinity.

According to this, it would be important to test different *Opuntia* species for tolerance to salinity, because through revegetation programs they could help to save vast areas from desertification. Tolerance of *Opuntia* spp. to salinity has been studied by Berry and Nobel (1985), Silverman et al.(1988), Nerd et al.

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(1991), Gersani et al. (1993), Nobel (1995), Le Houérou (1996, 2002), among others. Salt tolerance may be assessed by determining the degree of growth response to salinity (McCree and Richardson, 1987). To test this possibility on two forage *Opuntia* species, e.g. *O. spinulifera* Salm-Dyck f. *nacuniana* Le Houér., f. *nov*. and *O. robusta* Wendl., the purpose of the present study was to evaluate if they were suitable for eco-cultivation (cultivation in nonarable lands) in dry areas with access to underground saline water or in saline soils.

MATERIALS AND METHODS

Cladodes of the forage species *O. robusta* Wendl (Figures1 through 4) and *Opuntia spinulifera* Salm-Dyck f. *nacuniana* Le Houér. f. *nov* (Figures 5 through 8)*.,* previously measured and selected for uniformity (Table 1), were employed in a salt-stress assay conducted outdoors and planted in plastic pots 40-cm diameter and 50-cm height, filled with sandy soil. Before plantation, soil in pots was repeatedly moistened with saline solutions of different concentrations to salinize them. All solutions were prepared using Hoagland's nutrient solution (Hoagland and Arnon, 1950) that were diluted to 1/8 strength with tap water. To do this, sufficient amount of commercial sodium chloride was added to reach concentrations of approximately 25, 50, and 100 mmol NaCl. Solutions used for irrigation varied from non-saline (0 mmol NaCl) to very high saline (100 mmol NaCl) (U.S. Salinity Laboratory Staff, 1954; Nijensohn, 1961). We report the electrical conductivity (EC) of the soil saturation extracts.

Table 1. Some parametric determinations on detached mature cladodes of the two *Opuntia* species used in the assay which were measured and selected by several characteristics (data corresponded to means ±SE; n = 20)

Species	**Fresh Weight (g)**	**Dry Weight (g)**	**Degree of Succulence[1]**	**Water Storage Capacity (cm depth)[2]**
O. robusta	987 ±79	71 ±6	13.9 ±1.1	1.30 ±0.13
O. spinulifera	747 ±49	45 ±3	16.6 ±1.1	1.49 ±0.09

[1] Ratio Fresh weight/ Dry weight
[2] Ratio Volume/Area (two faces), ml cm^{-2}. It represents the average depth of the tissue from which water can be obtained to maintain the plant metabolism.

Once soils reached a salt concentration similar to that for the irrigation solutions, cladodes of both species were planted, one per pot. Irrigation thereafter was continued as required using the corresponding solution concentration, allowing or not to drain the excess liquid. From time to time irrigation was done with tap water (EC 0.82 dS m^{-1}). Pots were randomly arranged in four treatments with four replications of four pots per repetition. Controls were 1/8 strength Hoagland's.

During the course of the assay, mainly before or after irrigation, the fluctuations of salt concentration in the soil solution were followed by measurement of the EC of the soil saturation extracts. After approximately 7 months growth period, all plants were harvested and separated into young cladodes and roots. Cladodes were counted and roots were washed with tap water and then both were oven dried at 70ºC until no further change in weight was observed.

Analysis of variance procedure was used to test for differences in yield parameters for each species. Means were separated with Tukey's HSD test ($p < 0.05$). The standard error of the mean (SEM) was also calculated.

RESULTS

The salinity levels, either on irrigation solutions or those on the soil saturation extracts, are shown in Table 2. The initial soil salinity in the pots of 1.35 ±0.11 dS m^{-1} increased during the course of the salinity assay to reach high and even excessive saline condition (EC from 6.0 to 15.8 dS m^{-1}) levels. This was attributable to soil water evaporation that occurred between irrigations.

Table 2. Variations in the electrical conductivity (EC) acquired by soils during the course of the growing period of *O. spinulifera* and *O. robusta* irrigated with NaCl solutions of different concentrations

Irrigation Solution		**EC (dS m^{-1}) of Soil Saturation Extract**	
Concentration (mmol)	**EC (dS m^{-1})**	**Average ±SEM**	**Extreme Values Acquired**
0	0.84	1.57 ±0.33	0.50 - 3.12
25	3.20	5.05 ±1.11	2.10 - 9.43
50	5.71	6.87 ±1.40	2.78 - 12.05
100	10.04	10.73 ±1.32	6.01 - 15.75

As the concentration of applied NaCl solutions was increased, above-ground yield of both species was practically not altered with respect to the controls, until 50 mmol NaCl inclusive (Table 3). The same occurred with root yield *of O. robusta* while root yield of *O. spinulifera* was significantly affected at all NaCl tested levels. At 100 mmol NaCl irrigation regime, all yield parameters examined were significantly impaired. The decrease at this irrigation level in relation to their controls, for *O. robusta* and *O. spinulifera* respectively, were: for number of cladodes, 33 and 20%; for cladode dry biomass, 55 and 55%; and for root dry biomass, 70 and 61%.

Table 3. Yield parameters measured on *O. spinulifera* and *O. robusta* under several levels of soil salinity (SEM is shown between parentheses)

Species	Treatment (mmol NaCl)	Yield Parameters Plant^{-1}		
		Cladode		Root
		Number	Dry Weight (g)	Dry Weight (g)
O. robusta	0	2.25 (0.27) a	16.9 (2.3) a	9.4 (1.4) a
	25	1.94 (0.06) a	13.1 (1.6) a	7.5 (0.7) a
	50	2.25 (0.35) a	11.1 (1.3) a	5.7 (1.0) ab
	100	1.50 (0.27) b	7.6 (0.8) b	2.8 (0.5) b
O. spinulifera	0	1.56 (0.12) a	19.5 (2.5) a	26.0 (1.0) a
	25	1.75 (0.14) a	14.8 (1.7) a	18.8 (0.7) b
	50	1.44 (0.16) a	12.3 (0.8) ab	14.4 (1.3) c
	100	1.25 (0.10) b	8.8 (0.3) b	10.1 (0.5) d

Means in a column followed by the same letter, independently for each species, are not significantly different at $p < 0.05$ using Tukey's test.

DISCUSSION

Cacti are normally little tolerant to the presence of appreciable amount of dissolved salt in their root zone. The admitted lower limits correspond to an electrical conductivity of 5 to 6 dS m^{-1} in the saturation extract of the soil (Le Houérou, 1996, 2002). A possible explanation of that statement may be that the increase of sodium in the soil provokes a decrease of the net CO_2 uptake and the nocturnal acid accumulation, which affects the growth of cacti, including *Opuntias* (Nobel, 1983, 1994, 1995). The results of this study revealed that the fluctuating accumulation of high amount of salt in the potted soils did not cause serious detrimental effects on the above-ground yield of these two *Opuntia* species up to an EC average level of 6.9 dS m^{-1}, at least during 7-months treatment period. Nevertheless, the root systems were affected mainly in *O. spinulifera*. This result is not surprising since the roots of *Opuntias* are usually more affected than the shoots by increasing salinity. Watering *O. ficus-indica* for 6-months with 60 mmol NaCl solution reduced root growth by 84% and shoot growth by 50% (Nobel, 1995), and at NaCl concentration of only 25 mmol the growth of the same species was reduced by 50% (Berry and Nobel, 1985). A concentration of 30 mmol Na Cl reduced growth of individual roots of *O. ficus indica* by 40%, similar to the value obtained in this study at 50 mmol NaCl for the two studied species. At 100 mmol NaCl the root growth of *O. ficus-indica* was reduced by 93% (Nerd et al., 1991; Gersani et al., 1993), value higher than that reported in the present study (about 70% and 60% for *O. robusta* and *O. spinulifera*, respectively).

Many species of native plants from different arid and semiarid regions of Argentina have been documented to growth spontaneously in soils with different salinity levels, e.g., from medium (about EC of 8 dS m^{-1} of the soil saturation extract), elevated (8 to 16 dS m^{-1}) to excessive salinity (more than 16 dS m^{-1}) (Lemes, 1992; Cony, 1993). *Prosopis flexuosa* DC. and *P. chilensis* (Mol.) Stuntz. have been found to growth normally in soils with more than 50 dS m^{-1} (Cony, 1993). Other species of *Prosopis* showing high tolerance to salinity and alkalinity are *P. affinis* Sprengel, *P. alba* Gris., *P. caldenia* Burk., *P. ruscifolia* Gris., *P. pugionata* Burk., *P. alpataco* Phil. var. lamaro Roig, *P. sericantha* Gill. ex H. & A., *P. reptans* Benth., *P. nigra* Hieron., *P. strombulifera* Benth., *P. vinalillo* Stuck. and others (Roig, 1993). In addition, the shrub *Atriplex lampa* Gill. ex Moq. and the grasses *Trichloris crinita* (Lag.) Parodi, *Pappophorum caespitosum* R. Fries, *Digitaria californica* (Benth.) Henrard, and *Setaria leucopila* (Scribn. & Merr.) K. Schum. were found growing without any symptoms of toxicity in soils having between 10 and 36 dS m^{-1}, and even 64 dS m^{-1} for *T. crinita* (Lemes, 1992).

Aside from localized high saline sites, extended areas of the arid and semiarid Phytogeographic Province of Monte in Argentina present salinity levels classified, for crop plants, as medium saline (about 8 dS m^{-1}) (Braun Wilke, 1971; Lemes, 1992; Cony, 1993). Considering that the salinity level (extreme value of 12 dS m^{-1})) acquired by the soils irrigated with NaCl solution of 50 mmol did not provoke a significant decrease in the dry matter of cladodes produced by the two *Opuntia* species, they would have the potentiality to be ecocultivated successfully in these types of soils.

The mechanism to tolerate high salinity is not the same for the generality of plants due mainly to the great diversity, but in many cases there are striking similarities (Salisbury and Ross, 1969). Particularly, for *Opuntia* plants the capacity to tolerate salinity seems to depend largely on species, cultivar, and even provenance. For instance, within a population of *O. hemifusa*, a provenance from a marine site was more tolerant to increasing salinity than that of a provenance from an inland population (Silverman et al., 1988).

According to the U.S. Salinity Laboratory Staff (1954), forage crops with medium salt tolerance range from an EC of 4 to 12 dS m^{-1} for a 50% decrease in yield compared to yields on nonsaline soils under comparable growing conditions. On the basis of this criterion we may consider *O. robusta* and *O. spinulifera* as plants having a medium tolerance to soil salinity. However, *Opuntia spinulifera* may be consider as less tolerant to soil salinity than the previous one because the root yield was reduced with respect to the control by 20% at only 25 mmol NaCl. In spite of that, the remaining roots were able to support the same above-ground yield as the control. The studied species would be situated between these two extreme crops: bean (*Phaseolus vulgaris* L.), a salt-sensitive crop, in which many growth parameters decline at NaCl level less than 50 mmol (Meiri and Poljakoff-Mayber, 1970), and the very tolerant sugar beet (*Beta vulgaris* L.), which is not affected even at NaCl level of 350 mmol (Papp et al., 1983).

Though not investigated here, the degree of salt tolerance exhibited by these two *Opuntia* species may be explained by factors related to the increased osmotic potential of the soil solution provoked by the accumulation of salt. Among these factors we can mention: development of osmotic adjustment to increasing osmotic pressure of the medium (Bernstein, 1961); osmotic regulation based on electrolytes which must involve salt exclusion from the cytoplasm with osmotic adjustment affected by compatible osmolits (Serrano, 1996) or what is more likely, in succulent tissues the process may proceed by avoidance through dilution of salt concentration in their large vacuoles (Silverman et al., 1988). Anyway, data here obtained suggest that these *Opuntia* species appeared to be well suited for eco-cultivation either on saline soil with an EC up to 12 dS m^{-1} (extreme value acquired when the concentration of the irrigation solution was 50 mmol NaCl) or in nonsaline plots irrigated with relatively highly saline water like that coming from the water table.

Because salts are so mobile in the soil, it is difficult to establish actual levels of salinity during the growing period. It must be taken into account that sustained productivity would be possible under saline conditions provided that certain agronomic principles are observed if salt accumulated is not partially leached out by precipitations typical of an arid climate. For this reason, it is important to understand that "it is the salinity of the soil solution rather than that of the irrigation water that affects growth detrimentally" (Kelley et al., 1949).

REFERENCES

Bernestein, L. 1961. Osmotic adjustment of plants to saline media. I. Steady state. American Journal of Botany 48: 909-918.

Berry, W.L., and P.S. Nobel. 1985. Influence of soil and mineral stresses on cacti. Journal of Plant Nutrition 8: 679-696.

Braun Wilke, R.H. 1971. Condiciones agroecológicas de áreas incultas en el sud este mendocino. Deserta 2: 7-66.

Cony, M. 1993. Programa de conservación y mejoramiento de especies del género *Prosopis* en la Provincia Fitogeográfica del Monte, Argentina. In: Unidades de Botánica y Fisiología Vegetal del IADIZA (Eds.), Contribuciones Mendocinas a la Quinta Reunión Regional para América Latina y El Caribe de la Red de Forestación del CIID, pp. 37-71. Mendoza, Argentina: IADIZA-CRICYT-CIID. 153 pp.

Gersani, M., A. E. Graham, and P.S. Nobel. 1993. Growth response of individual roots of *Opuntia ficus-indica* to salinity. Plant Cell and Environment 16: 827-834.

Hoagland, D.R., and D.I. Arnon. 1950. The water culture method for growing plants without soil. California Agric. Exp. Stn., Circular 347: 1-32.

Kelley, W.P., B.M. Laurance, and D. Chapman. 1949. Soil salinity in relation to irrigation. Hilgardia 18: 635-665.

Le Houérou, H.N. 1996. The role of cacti (*Opuntia* spp) in erosion control, land reclamation, rehabilitation and agricultural development in the Mediterranean Basin. Journal of Arid Environments 33: 135-159.

Le Houérou, H.N. 2002. Cacti (*Opuntia* spp) as a fodder crop for marginal lands in the Mediterranean Basin. Acta Horticulturae 581: 21-46.

Lemes, J.L. 1992. Metodología en la exploración del recurso filogenético de forrajeras nativas. Xerophytia 3: 1-21.

McCree, K.J., and S.G. Richardson. 1987. Salt increases the water use efficiency in water stressed plants. Crop Science 27: 543-547.

Meiri, A., and A. Poljakoff-Mayber. 1970. Effect of various salinity regimes on growth, leaf expansion and transpiration rate of bean plants. Soil Science 109: 26-34.

Nerd, A., A. Karadi, and J. Mizrahi. 1991. Salt tolerance of prickly pear cacti (*Opuntia ficus-indica*). Plant and Soil 137: 201-207.

Nijensohn, L. 1961. Calidad de aguas para riego. In: U.N. de Cuyo, Instituto de Suelos y Riego (Eds.), Primer Curso Nacional de Manejo del Riego. Chacras de Coria, Mendoza: Facultad de Ciencias Agrarias.

Nobel, P.S. 1983. Nutrient levels in cacti in relation to nocturnal acid metabolism and growth. American Journal of Botany 70: 1244-1253.

Nobel, P.S. 1994. Remarkable Agaves and Cacti. New York: Oxford University Press. 165 pp.

Nobel, P.S. 1995. Environmental biology. In: Barbera, G., P. Inglese, and E. Pimienta-Barrios (Eds.), Agro-ecology, cultivation and uses of cactus pear, pp. 36-48. Rome, Italy: FAO. 216 pp.

Papp, J.C., M. C. Ball, and N. Terry. 1983. A comparative study of the effects of NaCl salinity on respiration, photosynthesis, and leaf extension growth in *Beta vulgaris* L. (sugar beet). Plant Cell and Environment 6: 675-677.

Roig, F.A. 1993. Informe nacional para la selección de germoplasma de especies de *Prosopis* de la República Argentina. In: Unidades de Botánica y Fisiología Vegetal del IADIZA (Eds.), Contribuciones Mendocinas a la Quinta Reunión Regional para América Latina y El Caribe de la Red de Forestación del CIID, pp. 1-36. Mendoza, Argentina: IADIZA-CRICYT-CIID. 153 pp.

Salisbury, F.B., and C. Ross. 1969. Plant Physiology. Belmont, California: Wadsworth Publishing Company, Inc. 747 pp.

Serrano, R. 1996. Salt tolerance in plants and microorganisms: toxicity targets and defense responses. International Review of Cytology 165: 1-52.

Silverman, F.P., D. R. Young, and P.S. Nobel. 1988. Effects of applied NaCl on *Opuntia hemifusa*. Physiologia Plantarum 72: 343-348.

United States Salinity Laboratory Staff. 1954. Saturated soil paste. Diagnosis and improvement of saline and alkali soils. Agricultural Handbook 60. Washington: USDA.

Figure 1. Entire plant of *Opuntia robusta* Wendl

Figure 2. Close-up view of cladode of *Opuntia robusta* Wendl

Figure 3. External view of fruits of *Opuntia robusta* Wendl

Figure 4. Internal view of *Opuntia robusta* Wendl fruit

Figure 5. Entire plant of *Opuntia spinulifera* Salm-Dyck f. *nacuniana* Le Houér. f. *nov.*

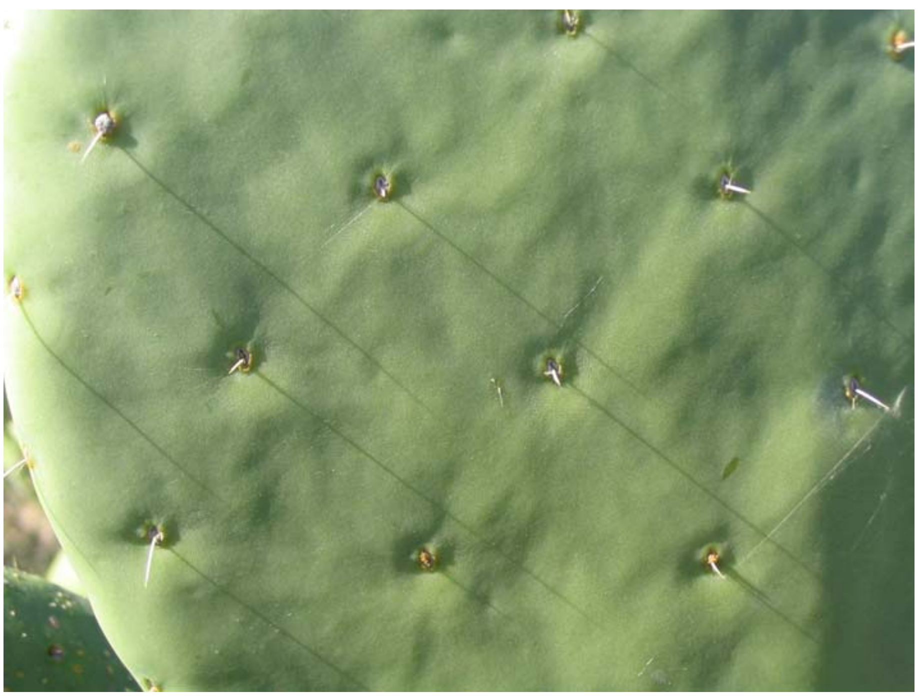

Figure 6. Close-up view of cladode of *Opuntia spinulifera* Salm-Dyck f. *nacuniana* Le Houér. f. *nov.*

Figure 7. External view of fruits of *Opuntia spinulifera* Salm-Dyck f. *nacuniana* Le Houér. f. *nov.*

Figure 8. Internal view of fruit of *Opuntia spinulifera* Salm-Dyck f. *nacuniana* Le Houér. f. *nov.*