Potential of Producing *Salicornia bigelovii* Hydroponically as a Vegetable at Moderate NaCl Salinity

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Abstract. *Salicornia bigelovii* is a halophyte that is capable of growing under high salinity. To evaluate the potential of producing *S. bigelovii* hydroponically as a vegetable at moderate NaCl concentrations, plants were grown in nutrient solutions with 6, 8, and 10 mM NaCl, and with 200 mM NaCl as a control. Results showed that plants had a reduced main stem length, canopy width, stem diameter, and root system length in 6 to 10 mM NaCl compared with those in 200 mM. Also, fresh weight increase, fresh and dry weights of individual plants, marketable yield, and water use efficiency of the plants grown in solutions with 6 to 10 mM NaCl were significantly lower than those grown in 200 mM. Associated with the reduced growth attributes, remarkable decreases in sodium uptake by the plants were also obtained in 6 to 10 vs. 200 mM NaCl. The results suggest that *S. bigelovii* is not a good candidate for hydroponic production as a vegetable at moderate NaCl salinity resulting from reduced growth attributes, which are possibly associated with decreased sodium uptake.

Hydroponic vegetable growers are searching for ways of reducing discharge and increasing on-farm reuse of drainage (Shannon and Grieve, 2000), because discharge wastes both water and fertilizer, pollutes the environment, and sometimes even results in soil salinization (Varlagas et al., 2010). One of the most important factors limiting the reuse of nutrient solutions for hydroponic production of common vegetables (e.g., cucumber, tomato, and pepper) is elevated salinity (Van Os, 1998), resulting mainly from Na⁺ and Cl⁻ accumulations attributable to differential ion uptake by these crops (Kronzucker and Britto, 2011; Savvas et al., 2005). An alternative strategy is to reuse these salinized solutions for hydroponic production of another economically valuable and more salt-tolerant crop (Grieve and Suarez, 1997; Kong and Zheng, 2014; Pardossi et al., 1999). It requires that this species has the ability to withstand elevated salinity levels without growth inhibition and reduced productivity while providing a saleable product (Adler et al., 2003; Grieve and Suarez, 1997).

Salicornia bigelovii has been listed as one of the most salt-tolerant species among 1560 halophytes and has been shown to maintain

normal growth even when soil NaCl concentration exceeds 1.3 M, two times greater than full-strength seawater salinity (≈500 mM NaCl; Glenn et al., 1999). Also, *S. bigelovii* has been introduced to U.S. and European fresh produce markets as a specialty vegetable where its succulent young shoots are sold as ‘Sampshire’ or ‘Sea asparagus’ and are in high demand in gourmet kitchens not only for their salty taste, but also for their high nutritional value (Ventura et al., 2011; Ventura and Sagi, 2013). *S. bigelovii* has been evaluated and cultivated commercially as a vegetable in Mexico, the Middle East, and Africa (Jaradat and Shahid, 2012; Ventura and Sagi, 2013; Zerai et al., 2010).

Can *S. bigelovii* be used for hydroponic production as a vegetable in the salinized discharged solutions mentioned before? Currently, limited information is available to answer this question. Grattan et al. (2008) has found that *S. bigelovii* has the potential to reuse hypersaline drainage water and that it is able to grow well at one-third strength to full-strength seawater salinity. In the previously mentioned study, the plants were evaluated under relatively high NaCl concentrations, i.e., ≈150 to 500 mM (Grattan et al., 2008). However, the NaCl concentration of most nutrient solutions discharged from hydroponic production of common vegetables ranges from 6 to 8 mM, a moderate NaCl salinity (Van Os, 1998). Some studies indicate that *S. bigelovii* inhabits the broadest range of salinity and has very little phenotypic response to salinity gradient (Dagar, 2005; Jaradat and Shahid, 2012). Also, the plants of this species have not shown significant differences in the growth rate and

biomass accumulation at a salinity between 0.5 and 10 ppt (≈9 and ≈180 mM NaCl, respectively) until 35 ppt (≈630 mM NaCl; Brown et al., 1999). Conversely, other studies suggest the optimal NaCl concentration for *S. bigelovii* growth ranges from 170 to 200 mM (Ayala and O’Leary, 1995; Webb, 1966) or 100 to 400 mM (Parks et al., 2002), and a suboptimal NaCl concentration of 5 mM can cause decreased plant growth associated with reduced sodium uptake (Ayala and O’Leary, 1995). Because the reported results differ, further research is needed to determine whether there will be significant reductions in plant growth and sodium uptake for *S. bigelovii* grown hydroponically at moderate NaCl concentrations (i.e., 6 to 10 mM).

The overall objective of this study was to evaluate the potential of producing *S. bigelovii* hydroponically as a vegetable at moderate NaCl concentrations, the salinity level of nutrient solution discharged from hydroponic production of common vegetables.

Materials and Methods

Plant materials and growing conditions.

The study was conducted in a greenhouse in the Edmund C. Bovey building at the University of Guelph, Guelph, Ontario, Canada (lat. 43°33′ N, long. 80°15′ W). Seeds of *S. bigelovii* (Serra Maris Company, Ninove, Belgium) were sown in a medium with a peat-perlite ratio of 1:1 by volume on 21 June 2013. One month after sowing, seedlings with a height of ≈3 cm were transplanted into rockwool cubes (1.5" Starter Plugs; Grodan Inc., Ontario, Canada), which were embedded in a Styrofoam disk floating on the nutrient solution in a plastic pot (14-cm top and 12-cm bottom diameters × 15 cm high). Each pot had one Styrofoam disk with four seedlings growing in individual rockwool cubes, except for the control pot, which had only a Styrofoam disk and four unplanted rockwool cubes. Each pot contained ≈1.5 L of solution with the following nutrients (mg·L⁻¹): 278.3 nitrogen, 36.7 phosphorus, 420 potassium, 97.6 calcium, 1.58 magnesium, 100.8 sulfur, 0.53 copper, 0.21 boron, 0.53 manganese, 0.53 zinc, 0.16 molybdenum, and 1.05 iron. Five days after transplanting, the nutrient solutions were changed for all the pots, and NaCl was added to the solutions to achieve four treatment concentrations: 6, 8, 10, and 200 (control) mM, which indicated the start of treatment. The initial Na⁺ concentrations of the four salt-treated nutrient solutions were measured as 6.8 ± 0.1, 8.7 ± 0.0, 10.6 ± 0.1, and 213.9 ± 3.3 mM, respectively, with the electrical conductivity of 3.38 ± 0.03, 3.52 ± 0.05, 3.75 ± 0.04, and 21.65 ± 0.70 dS·m⁻¹, respectively. The nutrient solutions were changed every 7 d to reduce nutrient and NaCl concentration variability during the experiment and to maintain a nutrient solution pH range of 5.5 to 7.0. Pots were arranged in a randomized block design with four blocks and four NaCl concentrations within each block.

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The greenhouse conditions were set at 18-h light/6-h dark by supplementing natural sunlight with high-pressure sodium lamps to achieve a photosynthetically active radiation at the canopy level averaging no less than $397 \pm 34 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and 22 to 28 °C light/20 to 22 °C dark with a relative humidity between 50% and 60%.

Measurements of plant growth and sodium uptake. Two plants were randomly chosen from each pot within each block for growth measurements. Every week the following attributes were measured: main stem length, node number and side branch number on the main stem, and canopy width. Four weeks after the start of treatment, seedlings were taken out of the solutions for photographing. The lengths of root systems and diameters of main stems and side branches were measured at the final harvest.

The fresh weight (FW) increase rate was determined weekly after the start of treatment until harvest. At harvest (28 d after the start of treatment), FW and dry weight (DW) of individual plants, marketable yield, and water use efficiency were estimated following the methods described by Kong and Zheng (2014).

Also at harvest, the total Na^+ removal amount (mmol/plant), water consumption (L/plant), Na^+ removal efficiency ($\text{mol}\cdot\text{kg}^{-1}$ DW), and Na^+ uptake concentration ($\text{mmol}\cdot\text{L}^{-1}$ H_2O) were evaluated following the same methods used by Kong and Zheng (2014).

Statistical analysis. Data were subjected to analysis of variance using DPS (Data Processing System) Software (Version 7.05; Refine Information Tech. Co., Hangzhou, China) and were presented as mean $\pm$ SE; separation of means was performed using Duncan's new multiple range test at the $P \leq 0.05$ level. Correlation analysis was used to determine the relationship between the parameters of Na^+ uptake and biomass accumulation.

Results

Plant growth. The plants grown in 6 to 10 mM NaCl had a smaller main stem length and canopy width 14 to 28 d after the start of treatment (Fig. 1A–B) when compared with those in 200 mM NaCl. However, throughout the experiment, the number of nodes and side branches on the main stem did not significantly differ among the four NaCl treatments (data not shown). At the time of harvest, plants grown in 6 to 10 mM NaCl appeared less succulent and had smaller plant canopies, shorter root systems, and thinner main stems and side branches compared with those in 200 mM NaCl (Table 1).

The FW increase rate was similar during the first week of treatment, but it was lower for plants in the 6 to 10 vs. 200 mM NaCl treatments during 7 to 28 d after the start of treatment (Fig. 2). Moreover, the difference in the FW increase rate between the 6 to 10 and 200 mM NaCl treatments increased over time (Fig. 2). At harvest, the FW and DW of individual plants, marketable yield, and water use efficiency of the plants grown in 6

Fig. 1. The temporal variation of main stem length (A) and canopy width (B) of *Salicornia bigelovii* grown in hydroponic solutions with different NaCl concentrations. Data are means $\pm$ SE ($n = 8$). Where bars are not visible, SE does not exceed the size of the symbol. The bars above the lines indicate least significant difference_{0.05} for each measuring day.

Table 1. Root system length, main stem diameter, and side branch diameter at final harvest for *Salicornia bigelovii* grown in hydroponic solutions with different NaCl concentrations.

Added NaCl concn (mM)	Root system length (cm)	Main stem diam (mm)	Side branch diam (mm)
6	$11.0 \pm 0.6^{\text{b}}$ ^a	2.23 ± 0.12 c	1.49 ± 0.17 b
8	11.3 ± 0.7 b	2.22 ± 0.13 c	1.65 ± 0.14 b
10	13.2 ± 1.3 b	2.55 ± 0.10 b	1.81 ± 0.10 b
200	24.2 ± 2.5 a	2.92 ± 0.08 a	2.31 ± 0.06 a

^aData are means $\pm$ SE ($n = 8$).

^bDifferent letters within a column denote significant differences ($P \leq 0.05$) according to Duncan's new multiple range test.

Fig. 2. Fresh weight (FW) increase rate at different times after the start of treatment for *Salicornia bigelovii* grown in hydroponic solutions with different NaCl concentrations. Data are means $\pm$ SE ($n = 4$). Bars bearing the same letter are not significantly different at $P \leq 0.05$ according to Duncan's new multiple range test.

to 10 mM NaCl were 3-fold lower than those in 200 mM NaCl (Table 2).

Sodium uptake. At final harvest, significant decreases were observed in sodium uptake and water consumption by plants when solution concentrations of NaCl decreased from 200 to 6 to 10 mM (Table 3). Plants exposed to 6 to 10 vs. 200 mM NaCl showed $\approx$ a 40-, 15-, and 30-fold decrease in Na^+ removal amount, Na^+ removal efficiency, and Na^+ uptake concentration, respectively, but less than a 2-fold reduction in water consumption.

Discussion

Moderate NaCl salinity inhibits plant growth of hydroponic *S. bigelovii*. High growth rate is one of the advantages of hydroponic production over soil cultivation

for leafy vegetables (Kaşkar et al., 2008). However, in the present study, *S. bigelovii* reduced plant growth (i.e., main stem length, canopy width, stem diameter, and root length) in 6 to 10 vs. 200 mM NaCl. This reduction would lead to a longer production period for *S. bigelovii* when grown under moderate vs. high NaCl concentrations.

Similar to our results, Ayala and O'Leary (1995) reported that hydroponic *S. bigelovii* showed a lower plant height in 5 vs. 200 mM NaCl and they attributed the reduced plant growth to toxic effects after hyperaccumulation of K^+ , Ca^{2+} , and Mg^{2+} by shoots to compensate for sodium deficiency. Also consistent with our results, their study indicated that plants grown at suboptimal salinity were less succulent and had significantly smaller stem diameters, possibly because of a reduction in cell size (Ayala and O'Leary, 1995).

Table 2. Fresh and dry weights, marketable yield, and water use efficiency 28 d after the start of treatment for *Salicornia bigelovii* grown in hydroponic solutions with different NaCl concentrations.

Added NaCl concn (mM)	Fresh wt (g/plant)	Dry wt (g/plant)	Marketable yield (kg·m ⁻²)	Water use efficiency (g fresh weight/L H ₂ O)
6	1.63 ± 0.16 ^a b ^y	0.21 ± 0.02 b	0.33 ± 0.03 b	5.39 ± 0.40 b
8	2.22 ± 0.10 b	0.26 ± 0.01 b	0.45 ± 0.02 b	7.13 ± 0.38 b
10	2.61 ± 0.39 b	0.28 ± 0.03 b	0.53 ± 0.08 b	7.81 ± 1.07 b
200	7.91 ± 0.93 a	0.71 ± 0.07 a	1.69 ± 0.21 a	20.98 ± 1.77 a

^aData are means ± SE (n = 4).

^yDifferent letters within a column denote significant differences ($P \leq 0.05$) according to Duncan's new multiple range test.

Table 3. Na⁺ removal amount, Na⁺ removal efficiency, Na⁺ uptake concentration, and water consumption 28 d after the start of treatment for *Salicornia bigelovii* grown in hydroponic solutions with different NaCl concentrations.

Added NaCl concn (mM)	Na ⁺ removal amount (mmol/plant)	Na ⁺ removal efficiency (mol·kg ⁻¹ dry weight)	Na ⁺ uptake concn (mmol·L ⁻¹ H ₂ O)	Water consumption (L/plant)
6	0.13 ± 0.00 ^a b ^y	0.64 ± 0.07 b	0.42 ± 0.01 b	0.30 ± 0.01 c
8	0.17 ± 0.00 b	0.67 ± 0.04 b	0.56 ± 0.01 b	0.31 ± 0.01 bc
10	0.21 ± 0.01 b	0.79 ± 0.07 b	0.65 ± 0.02 b	0.33 ± 0.01 b
200	6.95 ± 0.29 a	10.02 ± 0.70 a	18.63 ± 0.63 a	0.37 ± 0.01 a

^aData are means ± SE (n = 4).

^yDifferent letters within a column denote significant differences ($P \leq 0.05$) according to Duncan's new multiple range test.

Table 4. Correlation analysis among the parameters of Na⁺ uptake and biomass accumulation 28 d after the start of treatment for *Salicornia bigelovii* grown in hydroponic solutions with different NaCl concentrations.

Parameters	Fresh wt (g/plant)	Dry wt (g/plant)	Marketable yield (kg·m ⁻²)	Water consumption (L/plant)
Na ⁺ removal amount (mmol/plant)	0.99**	0.99**	0.99**	0.92*
Na ⁺ removal efficiency (mol·kg ⁻¹ dry weight)	0.99**	0.99**	0.99**	0.92*
Na ⁺ uptake concentration (mmol·L ⁻¹ H ₂ O)	0.99**	0.99**	0.99**	0.92*
Water consumption (L/plant)	0.96**	0.95*	0.96*	

^aData are expressed as correlation coefficient (r) values.

* or ** next to the data indicates that correlations are significant at $P \leq 0.05$ or 0.01, respectively.

The smaller cells may be a consequence of reduced turgor pressure resulting from a low vacuolar content of Na⁺ and Cl⁻, because Na⁺ and Cl⁻ may be preferentially accumulated in cell walls when availability of NaCl is limited (Rozema and Schat, 2013). In another species of the same genus, *Salicornia dolichostachya*, Katschnig et al. (2013) found that the growth rate of plants was 123% greater at 300 vs. 50 mM NaCl, but provided no explanation for this observation. It appeared that these *Salicornia* species might be considered "obligate halophytes," because they do not just tolerate high salinity levels, but also require considerable salinity levels to attain optimal growth (Rozema and Schat, 2013).

Contrary to our results, Brown et al. (1999) did not find that *S. bigelovii* grown in sand within draining containers reduced its growth rate in ≈ 9 vs. ≈ 180 mM NaCl. It has also been reported in some field studies that this plant species has shown minimal growth response across a broad salinity gradient (Dagar, 2005; Jaradat and Shahid, 2012). It is possible that the salt-stimulated (or sub-optimal salinity-reduced) growth could only be observed in hydroponic systems with precise and constant salinity levels in nutrient solutions, but not in well-drained sand-culture

systems nor in field studies (Rozema and Schat, 2013).

For leafy vegetables, yield potential greatly depends on biomass accumulation (Pan, 2008). In the present study, hydroponic *S. bigelovii* showed a significantly lower biomass accumulation, resulting in a substantially lower marketable yield at 6 to 10 vs. 200 mM NaCl, which is not consistent with the research result under sand culture reported by Brown et al. (1999), possibly as a result of the difference in culture systems (Rozema and Schat, 2013). However, the similar reduction of plant growth at 6 to 10 vs. 200 mM NaCl in our experiment is tenable, because biomass accumulation is tightly linked to other growth attributes (Pan, 2008).

Similar to our results, Ayala and O'Leary (1995) found that the DW increase rate and the final fresh and dry mass of *S. bigelovii* plants grown in 5 mM NaCl were significantly lower than those grown in 200 mM NaCl. They also demonstrated that the reduced biomass accumulation in 5 vs. 200 mM NaCl-grown plants was not the result of an insufficient supply of photosynthates to support growth. Nevertheless, the reduced succulence (i.e., amount of water per unit dry

mass), also supported by our study (Table 2), could be a major contributor to decreased fresh biomass when this halophyte is grown at a moderate salinity (Flowers and Colmer, 2008). Succulence might not only be a mechanism to dilute excess NaCl in leaf tissues (Glenn et al., 1999), but could also be a prerequisite for salt-stimulated growth of plants grown in a hydroponic system (Rozema and Schat, 2013).

Also, significantly lower water use efficiencies (fresh biomass accumulation based on water consumption) was observed for *S. bigelovii* in the 6 to 10 vs. 200 mM NaCl treatments in our study. Previous studies have reported that halophytes could increase their water use efficiency in response to increased salinity, thereby minimizing the amount of water that must be transpired for each unit of growth (Ayala and O'Leary, 1995; Glenn et al., 1997, 1999). This finding implies that producing *S. bigelovii* in 6 to 10 vs. 200 mM NaCl would require increased water consumption for similar yields and non-enhanced water conservation in crop production.

Decreased Na⁺ uptake in hydroponic S. bigelovii at moderate NaCl salinity possibly contributes to reduced biomass accumulation. The ability to accumulate NaCl for osmotic adjustment is a nearly universal trait of salt-tolerant plants (Glenn et al., 1999). For example, *Salicornia* spp. under hypersaline conditions can accumulate salt up to 37% to 52% of dry mass in its shoot tissues (Grattan et al., 2008; Ushakova et al., 2005). However, Na⁺ uptake from the medium by plants was positively related to the NaCl concentration of root-zone solution, which might also affect the relative availability of Na⁺ to the plant root system (Teixeira and Carvalho, 2008). Consequently, in the present study, when the external NaCl concentration decreased from 200 to 6 to 10 mM, *S. bigelovii* significantly reduced Na⁺ absorption (Table 3).

Also, a positive correlation was observed among Na⁺ uptake, water consumption, and biomass accumulation (Table 4), suggesting the decreased Na⁺ uptake in *S. bigelovii* at moderate NaCl salinity is possibly associated with reduced water consumption and biomass accumulation. Halophytes use the controlled uptake of Na⁺, balanced by Cl⁻ and other anions, into cell vacuoles to drive water uptake into the plant against a low external water potential (Glenn et al., 1999). Consequently, when the external NaCl concentrations decreased from 200 to 6 to 10 mM, *S. bigelovii* not only decreased Na⁺ absorption, but also reduced water consumption (Table 3). Decreased water uptake by plants can directly result in reduced succulence and eventually in decreased biomass accumulation, because, as mentioned before, succulence can contribute greatly to biomass accumulation in halophytes (Flowers and Colmer, 2008; Rozema and Schat, 2013). Also, a previous study indicated that reductions in plant Na⁺ absorption were greater in hydroponic systems than in soil with a similar decrease of external NaCl concentration

(Tavakkoli et al., 2010). This difference may partly explain the suboptimal salinity-reduced growth that could only be observed in hydroponic systems but not in field soil studies.

In summary, our results suggest that at moderate NaCl salinity *S. bigelovii* is not a good candidate for hydroponic production as a vegetable as a result of decreased plant growth. Perhaps, the solutions with moderate NaCl concentrations (6 to 10 mM) could be used first for hydroponic production of moderate salt-tolerant plant species such as purslane and then for high salt-tolerant plant species such as *S. bigelovii* when the Na⁺ concentration accumulates to ≈200 mM.

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