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Evaluation of the halophyte *Salsola soda* as an alternative crop for saline soils high in selenium and boron

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ABSTRACT

Urbanization, industrial development, and intensive agriculture have caused soil contamination and land degradation in many areas of the world. Salinization is one important factor contributing to land degradation and it affects agricultural production and environmental quality. When salinization is combined with soil pollution by trace elements, as it occurs in many arid and semi-arid regions around the world, strategies to phyto-manage pollutants and sustain crop production need to be implemented. In this study, we present the case of saline soils in the West side of Central California which contain naturally-occurring selenium (Se), boron (B), and other salts, such as NaCl, $CaCl_2$, Na_2SO_4, and Na_2SeO_4. To sustain crop production on Se- and B-laden arid saline soils, we investigated the potential of the halophyte "agretti" (*Salsola soda* L.) as an alternative crop. The aim of our greenhouse study was to examine adaptability, B tolerance, and Se accumulation by *S. soda* grown on soils collected from a typical saline-laden field site located on the West side of the San Joaquin Valley (SJV). Our results showed that *S. soda* tolerates the saline (EC ~ 10 dS m^{-1}) and B-laden soils (10 mg B L^{-1}) of the SJV even with the additional irrigation of saline and B rich water (EC ~ 3 dS m^{-1} and 4 mg B L^{-1}). Under these growing conditions, the plant can accumulate high concentrations of Na (80 g Na kg^{-1} DW), B (100 mg B kg^{-1} DW), and Se (3–4 mg Se kg^{-1} DW) without showing toxicity symptoms. Hence, *S. soda* showed promising potential as a plant species that can be grown in B-laden saline soils and accumulate and potentially manage excessive soluble Se and B in soil.

1. Introduction

Loss of productive land due to abiotic stresses (i.e. drought, increased salinity, and soil pollution) is posing major challenges to provision of nutritious and safe food, sustainability of agriculture, and conservation of agro-ecosystems and environmental quality. Salinization combined with recurrent droughts and higher uncertainty in climate stability represents a serious threat to agricultural production in many regions around the globe (e. g., United States, China, Australia, Bangladesh, India, etc.). Salinization combined with occurrence of trace elements, as in salt marshes and in arid-saline areas where the soil is naturally rich in trace elements, requires implementation of management strategies for sustainable crop production and protection of water quality.

For example, farming traditional and alternative crops in saline, arid and poor quality soils may be considered one of the potential strategies to sustain the current and future global food system. One possible strategy to manage high levels of soluble trace elements is to firstly identify drought and salt tolerant crops that can survive such poor growing conditions, and then use the plants to extract soluble trace elements (i.e. Se and B) from the soils (Bañuelos, 1996).

Many soils in the Western United States, e.g. West side of central California, are derived from Cretaceous shale rock and contain naturally-occurring selenium (Se), boron (B), and other salts, such as sodium chloride (NaCl), calcium chloride ($CaCl_2$), sodium sulfate (Na_2SO_4), and sodium selenate (Na_2SeO_4) (Schoups et al., 2005). In the West side of central California excessive accumulation of Se and B in the groundwater was caused by a combination of geology, salinity, intensive irrigation practices, and lack of tile drainage system (Presser and Schwarzbach, 2008). In the past, inefficient irrigation delivery systems contributed to solubilization and

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redistribution of those natural-occurring trace elements and other salts within the soil profile. Excessive concentrations of soluble trace elements, i.e., B, Se, have proven to be damaging to their surrounding eco-environment, including both plants and biological systems (Ohlendorf et al., 1986). Other similar areas within the Western USA, i.e., Colorado, Wyoming, Nevada, and Montana, were also concerned about similar ecological disasters occurring within their respective susceptible regions, due to high levels of soluble B, Se, and other trace elements present in their soils. In the west side of central California, indian mustard (*Brassica juncea*) and canola (*Brassica napus* L.) are two of the most common plants species utilized for phyto-managing B- and Se-laden saline soils (Bañuelos, 2001). Plant species used for the phyto-management of soluble ions in arid saline soils must tolerate high levels of salinity and B and accumulate naturally occurring Se from the soil. In regard to salt and B tolerance, salt-tolerant plants (halophytes) may satisfy this requirement and thus making halophytes optimal candidates for the phyto-management of soluble ions in trace element laden saline soils.

Salsola soda L., more commonly known as 'agretti' (Fig. 1), is a halophyte native to the Mediterranean basin. It is a relatively small plant that grows to about 0.7 m on average in coastal regions and can be irrigated with salt water. Throughout history, the plant was a very important source of soda ash, as people would extract the ashes from *S. soda*. The plant is no longer grown for the use of its soda ash but rather it is farmed as a vegetable. In folk medicine, *Salsola* species are traditionally used for the treatment of hypertension, constipation and inflammation (Tundis et al., 2009). In this regard, alkaloid extracts from *Salsola* species have been evaluated for the treatment of Alzheimer's disease (Tundis et al., 2009).

S. soda has been studied by Colla et al. (2006) and Graifenberg et al. (2003) as a "biodesalinating companion plant" to tomatoes and peppers in saline soils in central Italy. The authors showed that pepper and tomatoes respectively grown together with *S. soda* had a higher yield than if grown alone as monocrop. They attributed the higher yields to the ability of the halophyte 'agretti' to accumulate Na and reduce sodium's impact on pepper and tomatoes.

S. soda is a halophyte that is cultivated in Italy where it is consumed as a vegetable and it is offered in gourmet restaurants in Europe and America. The plant was recently documented as one of the endemic species in alkali grasslands typical of Central and Eastern Europe such as those in the Carpathian-basin (Török et al., 2012). Recent studies have shown the potential use of *S. soda* for the phytostabilization of polluted areas, as it can accumulate moderate levels of trace metals (Milić et al., 2012; Lorestani et al., 2011).

This study evaluates the potential of growing *S. soda* in B- and Se-laden soils of the west side of central California as both an alternative food crop and as potential species for phyto-management of Se and B in saline soils.

The aim of our study was to evaluate adaptability, salt and B tolerance, and Se accumulation by *S. soda* grown on typical unproductive saline soils collected from the west side of central California (Five Points, CA). We hypothesized the following: a) *S. soda* will be able to tolerate B and the salts present in the soil and safely accumulate potentially plant toxic ions, i.e., Na, Cl, and B, and b) *S. soda* will accumulate Se in the above ground biomass.

2. Materials and methods

2.1. Greenhouse pot experiment

Seeds of *S. soda* were purchased from the commercial retailer 'Seeds from Italy' (Lawrence, KS). The seeds were pre-germinated on potting soil and in plastic flats for 18 days. The germination potential of the seeds was about 65%. Seeds were watered daily twice a day with low saline water (electrical conductivity (EC) < 0.5 dS m^{-1}). The experiment was carried out under greenhouse conditions at SJV Agricultural Research Center in Parlier, CA. Greenhouse conditions were as follows: day/night temperatures 28/20 °C, 16 h photoperiod, 40–50% relative humidity of ambient air, and an average daily 200 μmol photons m^{-2} s^{-1} minimum light intensity. After 18 days, seedlings were transplanted into 2 kg pots filled with two types of typical west (saline) and east side (non-saline) soils of Central California. The saline soils consisted of an Oxalis silty clay loam (fine montmorillonitic, thermic Pachic Haploxeral with a well-developed salinity profile) collected at Red Rock Ranch (Five Points, CA), while the non-saline soil (designated as control) consisted of a Hanford sandy loam (coarse-loamy, mixed superactive, nonacid, thermic Typic Xerothents) soil collected at the SJV Agricultural Research Center in Parlier, CA. Chemical characteristics of the two soils (saline and control) are described in Table 1 and in Bañuelos (2002) and in Bañuelos and Lin (2010), respectively.

Treatments on saline and control soils were as follows: treatment 1 (T1): saline soil from Red Rock Ranch with EC of 10 dS m^{-1} and water soluble B of 10 mg L^{-1}; treatment 2 (T2): saline soil from Red Rock Ranch with EC 10 dS m^{-1} and water soluble B of 10 mg L^{-1} + irrigation with saline solution (described below and in Table 1); treatment 3 (T3): non-saline control soil from SJV Agricultural Research Center with EC of 2.3 dS m^{-1} and water soluble B of 0.12 mg L^{-1}; and treatment 4 (T4): non-saline control soil from SJV Agricultural Research Center with EC of 2.3 dS m^{-1} and water soluble B of 0.12 mg L^{-1} + irrigation with saline solution (described below and in Table 1). Five replications per treatment were used and the pots were placed in the greenhouse in a complete randomized block design. For each treatment, three pots without plants were also added and treated similarly as the planted pots within each treatment. Soil EC and pH were measured in both

Fig. 1. Wild *S. soda* growing on the coast near the sea water (left) and cultivated *S. soda* known as 'agretti' vegetable (right).

Table 1
Description of treatments used in the study and selected chemical characteristics of the soils used. Data represent average of three replicates and standard error in brackets.

Treatment name	Quality of irrigation water	Soil EC ($dS\ m^{-1}$)[c]	pH	Water extractable boron[d] ($mg\ L^{-1}$)	Water extractable selenium[d] ($mg\ L^{-1}$)	Water extractable sodium[d] ($mg\ L^{-1}$)
T1[a]	Deionized water	10.2 (0.6)	8.02 (0.06)	10.45 (0.25)	0.2 (0.003)	1469 (0.2)
T2[a]	Saline solution[e]	10.2 (0.6)	8.02 (0.06)	10.45 (0.25)	0.2 (0.003)	1469 (0.2)
T3[b]	Deionized water	2.3 (0.5)	7.68 (0.03)	0.12 (0.004)	0.002 (0.000)	96.7 (9.4)
T4[b]	Saline solution[e]	2.3 (0.5)	7.68 (0.03)	0.12 (0.004)	0.002 (0.000)	96.7 (9.4)

[a] Soil type: Oxalis silty clay loam.
[b] Soil type: Hanford sandy loam.
[c] Values of electrical conductivity (EC) at the start of the experiment.
[d] Water extractable concentrations of B, Se, and Na at the start of the experiment.
[e] Applied 2 weeks after transplanting; the saline solution had an electrical conductivity of 3.2 $dS\ m^{-1}$ comprised of $CaCl_2$, NaCl, and Na_2SO_4 and 0.250 mg Se L^{-1} as Na_2O_4Se and 4 mg B L^{-1} as H_3BO_3.

planted and unplanted pots at time 0 (before transferring the plants into the pots) and at harvest.

For the first week of the experiment, all pots were watered twice a day with a total 60 mL per day of low salinity water (EC < 0.5 $dS\ m^{-1}$). The amount of water applied was reduced to a total 30 mL per day in the second week of the experiment to maintain soil moisture at about 15% and to simulate a moderate water stress for each treatment. Irrigation water was added to drainage saucers to avoid leaching and to assure homogenous wetness of the soil. Two weeks after transplanting, treatments 2 and 4 received saline solution as source of irrigation water (Table 1). The saline solution added as irrigation had electrical conductivity of 3.2 $dS\ m^{-1}$, which was comprised of $CaCl_2$, NaCl, and Na_2SO_4 salts, 0.250 mg Se L^{-1} as Na_2O_4Se and 4 mg B L^{-1} as H_3BO_3. Salts and B composition of saline solution represents a typical lower quality groundwater oftentimes present in the west side of Central California. The saline solution was applied three days a week for three weeks, while 30 mL of low salinity water (EC < 0.5 $dS\ m^{-1}$) were applied to each pot on the other 4 days of the week. Plants were not fertilized.

Shoot height was recorded weekly by measuring the length of shoot from top to 0.5 cm from soil surface. Plants were monitored weekly for insect infestation and for the appearance of any toxicity and/or deficiency symptoms.

2.2. Harvest

All plants were harvested 30 days after transplanting, irrespective of treatment. Shoots were cut 1 cm above soil surface, weighed, washed in deionized water, and patted dry prior to drying in the oven at 55 °C for at least five days. The soil from each pot was emptied out onto a dry surface, mixed thoroughly and sampled randomly to collect approximately two bags from each pot, each containing 150 g of moist soil for analysis of: 1) total and water extractable mineral elements, and 2) pH and EC. Prior to analysis, soil samples were oven dried at 55 °C for at least five days. All soils and shoot samples were weighed and then ground in a stainless steel Wiley mill equipped with a 0.83 mm screen before being acid digested for mineral analysis (described below). Plant roots were not collected because the root system is very fine and it was very difficult to wash the soil particles off the roots without breaking them.

2.3. Water soluble mineral elements, chloride, electrical conductivity, and pH

Water soluble elements concentrations (expressed as mg L^{-1}), chloride, salinity [electrical conductivity (EC); $dS\ m^{-1}$] and pH were determined in a 1:1 soil-water extract. Water soluble Se was analyzed using an Agilent ICP-MS (Santa Clara, CA) and other soluble ions were measured using Varian Vista ICP-OES (Palo Alto, CA) after preparing the samples, as described by Bañuelos and Meek (1990). Soil EC was measured at room temperature using an Orion Model 150 Conductivity Meter (Thermo Scientific, Waltham, USA), chloride analysis was performed at room temperature with a Mettler Toledo Titrator (Mettler Toledo, Columbus, OH, USA), and pH was determined at room temperature using an Orion 420A pH meter (Thermo Scientific, Waltham, USA).

2.4. Total mineral elements

A standard procedure was used to determine the mineral element concentrations in *S. soda* shoot and soil samples (Bañuelos and Lin, 2010). Plant tissues were wet digested with HNO_3–H_2O_2–HCl, as described by Bañuelos and Akohoue (1994). NIST coal fly ash (SRM 1633; Se content of 10.3 ± 0.6 mg kg^{-1}, with a recovery of 93%) and NIST wheat flour (SRM 1567; Se content of 1.1 ± 0.2 mg kg^{-1}, with a recovery of 94%) were used as an external quality control standard for the soil and plant material, respectively. Selenium and other elements were analyzed by an inductively-coupled plasma optical emission spectrometer (Agilent 7500cx, Santa Clara, USA) according to Agilent manufacture protocol.

2.5. Statistical analysis

All data were analyzed using the SAS package (Institute S, 1989). The Proc Mixed procedure was used for analysis of variance to determine difference between treatments. Significance was set at the 5% level.

3. Results and discussion

Concentrations of total and water soluble B, Ca, Cl, Mg, Na, S, and Se were higher in the saline soil (T1 and T2) than in control soil (T3 and T4) (Tables 2 and 3) at harvest, while concentrations of K, P, and Zn were higher in control soils compared to saline soils at harvest (Tables 2 and 3), and Fe, Mn, and Cu were similar in both saline and control soils. Water extractable B, Na and Se concentrations were significantly higher at harvest in control soils (T4) after irrigation with saline solution compared to the control soil irrigated with low saline water (T3) (Tables 2 and 3). In both saline soil (T1 and T2) and control soil treatments (T3 and T4), pH values were higher in planted pots at harvest than before planting (time 0, Fig. 2), indicating that pH was affected by the plant. In the saline soil treatments (T1 and T2) the pH values were higher in the unplanted pots at harvest than at time 0, probably due to irrigated-induced solubilization of salts during the experiment. Soil EC at harvest was similar to soil EC before planting (time 0) in both planted and unplanted pots (data not shown) in all treatments.

Irrespective of treatment, the plants were healthy throughout

Table 2
Water extractable (g or mg L^{-1}) and total (g or mg kg^{-1}) concentrations of mineral elements (Ca, Fe, K, Mg, Mn, Na, P, and S) in soil at harvest. Values represent average (n = 5) with standard error (SE) in brackets. Asterisk (*) indicate statistical significance ($P \leq 0.05$).

Element	T1[a]	T2[a]	T3[a]	T4[a]
Ca (g L^{-1})	0.89 (0.01)	0.53 (0.00)	0.06 (0.00)	0.07 (0.00)
Ca (g kg^{-1})	16.26 (0.25)	17.37 (0.46)	4.05 (0.12)	3.87 (0.11)
Fe (mg L^{-1})	0.41 (0.01)	0.41 (0.01)	0.90 (0.11)	0.45 (0.02)
Fe (g kg^{-1})	20.83 (0.21)	21.66 (0.25)	18.51 (0.32)	18.69 (0.72)
K (mg L^{-1})	41.53 (9.77)	43.31 (7.62)	192.56 (7.95)	189.69 (19.14)
K (g kg^{-1})	2.83 (0.07)	2.76 (0.1)	3.55 (0.04)	3.71 (0.1)
Mg (mg L^{-1})	92.98 (3.33)	74.88 (2.21)	19.99 (1.87)	21.88 (1.06)
Mg (g kg^{-1})	11.94 (0.1)	12.03 (0.22)	3.74 (0.04)	3.84 (0.07)
Mn (mg L^{-1})	0.03 (0.01)	0.02 (0.00)	0.09 (0.02)	0.10 (0.02)
Mn (g kg^{-1})	0.27 (0.00)	0.30 (0.00)	0.27 (0.00)	0.28 (0.00)
Na (g L^{-1})	1.47 (0.09)	1.41 (0.05)	0.02 (0.00)	0.04* (0.00)
Na (g kg^{-1})	2.94 (0.11)	2.64 (0.88)	0.17 (0.04)	0.16 (0.00)
P (mg L^{-1})	0.16 (0.09)	0.02 (0.02)	9.76 (1.66)	6.96 (0.43)
P (g kg^{-1})	0.76 (0.03)	0.64 (0.04)	1.68 (0.05)	1.33 (0.31)
S (g L^{-1})	1.57 (0.13)	1.06 (0.02)	0.04 (0.00)	0.05 (0.01)
S (g kg^{-1})	6.10 (0.11)	5.99 (0.25)	0.17 (0.02)	0.16 (0.01)

*T4 statistically different ($P \leq 0.05$) than T3, no statistical difference was observed between T1 and T2 for the same element.
[a] See Table 1 for description of treatments.

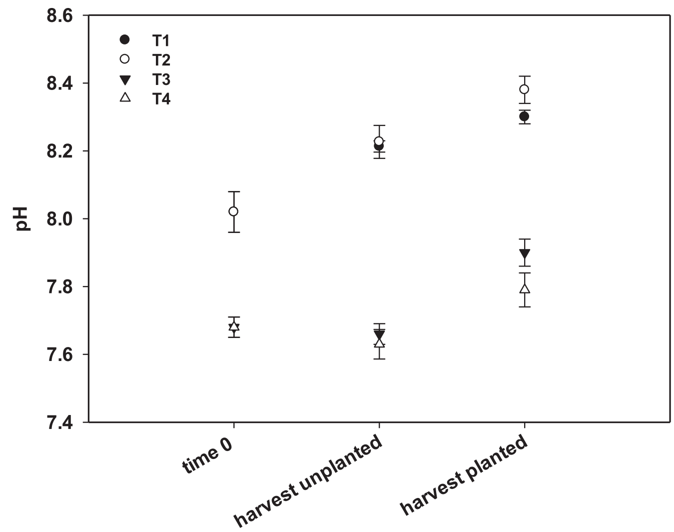

Fig. 2. Soil pH measured at time 0 (before transplanting the plants into the pot) and in unplanted and planted pots at harvest. Values represent average of five replicates and error bars represent SE. (T1: soil with EC of 10 dS m^{-1}, T2: soil with EC 10 dS m^{-1} + saline solution, T3: control soil, and T4: control soil + saline solution; see Table 1).

the experiment and they did not show any visual deficiency and toxicity symptoms despite receiving no fertilizer for 30 days. *S. soda* showed significantly higher shoot biomass, both fresh and dry, when grown on saline soil (fresh weight (g): 29.1 ± 0.8 T1 and 29.9 ± 0.9 T2; and dry weight (g): 4.6 ± 0.5 T1 and 5.4 ± 0.4 T2) relative to control soil (fresh weight (g): 16 ± 1.1 T3 and 17.3 ± 0.3 T4; dry weight (g): 2.7 ± 0.2 T3 and 2.6 ± 0.2 T4). This observation indicates that *S. soda*, as halophyte, may require or utilize salts to thrive and produce higher biomass. *S. soda* is a succulent and therefore the difference between fresh and dry weight biomass was large.

The shoot height was similar amongst all treatments each week but significantly increased with time for each treatment (Fig. 3). The percent increases were 54, 49, 42, and 47% after four weeks for saline soil (T1 and T2) and control soil (T3 and T4), respectively. As the level of soil salinity increases, a salt-induced water stress may occur in plants due to competition for water that is more tightly held by a saline soil.

Concentrations of Ca, K, Mg, and P were significantly higher in plant shoots grown on the control soil (T3 and T4) than in the saline soil (T1 and T2) (Fig. 4). At harvest, concentrations of total and water soluble P were significantly higher in control soil compared to saline soil (Table 2).

Concentrations of total and water soluble Ca and Mg were higher in saline soil at harvest, whereas total and water extractable concentrations of K in soil were higher in control soil at harvest (Table 2). The lower uptake of K, Ca and Mg in plants grown on saline soil relative to plants grown on control soil can be due to the selective preference for uptake of Na and Cl by *S. soda* from the saline soil, which contains higher concentrations of Na and Cl than control soil. Concentrations of Ca and Mg in the plants grown on saline soils are comparable to those reported by Watson and O'Leary (1993) for the various halophyte species grown on saline-alkaline field soils in the west side of the SJV. Similar results were also obtained by Díaz et al. (2013) who evaluated the performance of six different halophytes irrigated with saline drainage water in the west side of the SJV. They found that two plant species, *Distichilis spicata* L. and *Allenrolfea occidentalis* S. Wats., had similar Ca

Table 3
Water extractable (g or mg L^{-1}) and total (g or mg kg^{-1}) concentrations of mineral elements (B, Cl, Cu, Se, and Zn) in soil at harvest. Values represent average of 5 replicates and standard error (SE) in brackets. Asterisk (*) indicate statistical significance at $P \leq 0.05$.

Element	T1[a]	T2[a]	T3[a]	T4[a]
B (mg L^{-1})	13.48 (1.06)	9.87 (0.14)	0.05 (0.00)	0.13* (0.02)
B (mg kg^{-1})	66.05 (1.8)	69.78 (1.87)	3.40 (0.07)	2.37 (0.2)
Cl (g L^{-1})	1.20 (0.16)	1.10 (0.12)	0.45 (0.01)	0.45 (0.03)
Cu (mg L^{-1})	0.04 (0.00)	0.04 (0.01)	0.07 (0.01)	0.05 (0.00)
Cu (mg kg^{-1})	23.09 (0.37)	24.99 (0.49)	28.09 (0.27)	31.76 (0.85)
Se (mg L^{-1})	0.22 (0.02)	0.22 (0.02)	0.00 (0.00)	0.02* (0.00)
Se (mg kg^{-1})	2.76 (0.08)	2.69 (0.09)	0.10 (0.01)	0.10 (0.00)
Zn (mg L^{-1})	0.00 (0.00)	0.01 (0.01)	0.04 (0.02)	0.05 (0.02)
Zn (mg kg^{-1})	80.91 (0.68)	83.80 (1.6)	111.06 (4.34)	122.17 (9.85)

*T4 statistically different ($P \leq 0.05$) than T3, no statistical difference was observed between T1 and T2 for the same element.
[a] See Table 1 for description of treatments.

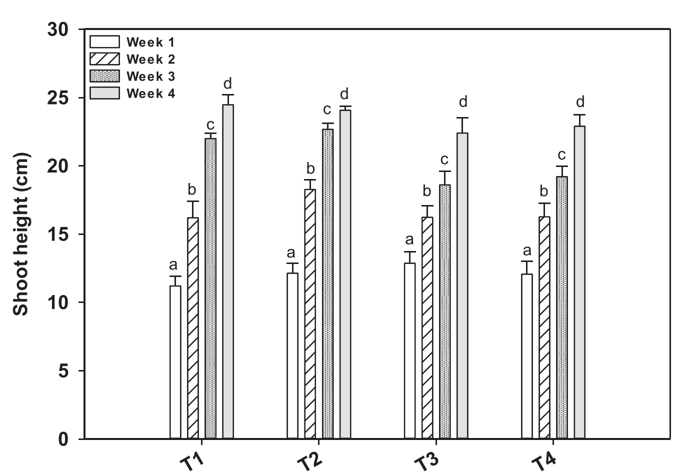

Fig. 3. Shoot height measured once a week for four weeks; measurements of height were started when the plants were 20 days old. Values represent average of 5 replicates and error bars represent SE. Similar letters indicate no statistical ($P \leq 0.05$) difference between treatments. (T1: soil with EC of 10 dS m^{-1}, T2: soil with EC 10 dS m^{-1} + saline solution, T3: control soil, and T4: control soil + saline solution; see Table 1).

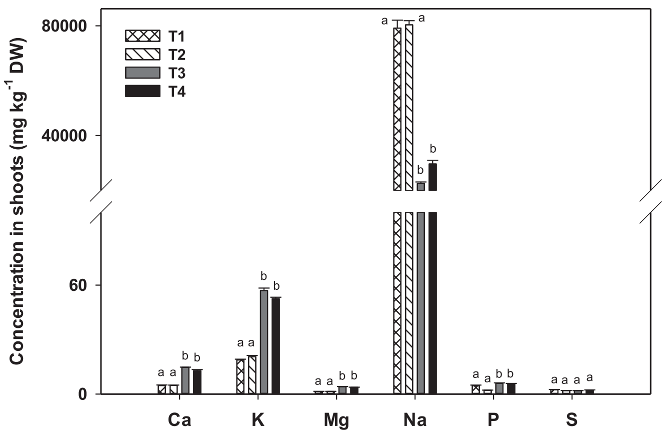

Fig. 4. Concentrations of Ca, K, Mg, Na, P, and S in *S. soda* shoot at harvest after 30 days from transplanting. Values represent average of 5 replicates and error bars represent SE. Similar letters indicate no significant ($P \leq 0.05$) difference between treatments for each element listed. (T1: soil with EC of 10 dS m^{-1}, T2: soil with EC 10 dS m^{-1} + saline solution, T3: control soil, and T4: control soil + saline solution; see Table 1).

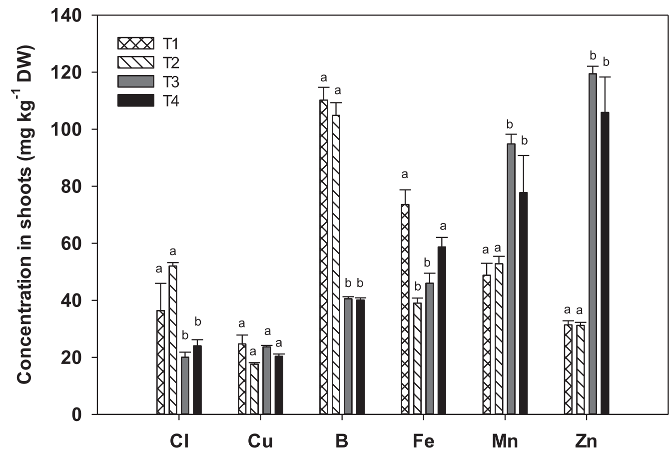

Fig. 5. Concentration of Cl, Cu, B, Fe, Mn, and Zn in *S. soda* shoot at harvest 30 days after transplanting. Values represent average of 5 replicates and error bars represent SE. Similar letters indicate no significant ($P \leq 0.05$) difference between treatments for each element listed. (T1: soil with EC of 10 dS m^{-1}, T2: soil with EC 10 dS m^{-1} + saline solution, T3: control soil, and T4: control soil + saline solution; see Table 1).

and Mg concentrations in shoots compared to those concentrations obtained in *S. soda* grown on saline soil in our study. Milić et al. (2013) reported comparable concentrations of Na, Ca, K, and Mg in shoots of *S. soda* grown in saline areas in the Republic of Serbia, indicating that the plant accumulated more Na than K, Mg, and Ca with a decreasing uptake of the ions in the order of Na >> K > Ca > Mg.

S. soda grown on saline soil (T1 and T2) accumulated 8% Na (Fig. 4) in dry matter, which is comparable to values obtained in *Atriplex* species (Watson and O'Leary, 1993) but lower than those obtained in dwarf saltwort (*Salicornia bigelovii*) grown on saline soil in the SJV (Díaz et al., 2013). In our study, an almost linear relationship was observed between water extractable soil Na and the Na concentration in shoots at harvest for all treatments with a Pearson correlation coefficient of $r = 0.96$ ($P \leq 0.05$).

Our results demonstrate that *S. soda* accumulates and tolerates very high levels of Na in the shoots, a characteristic needed for a plant to be considered as a viable alternative crop for the arid saline soils as those of the central west SJV. Similarly, the uptake of Cl in plants grown on saline soil (T1 and T2) was significantly greater than in control soils (T3 and T4) (Fig. 5), due to the significantly higher concentrations of Cl in saline soil (T1 and T2) (Table 3). Chloride concentrations in shoot are comparable to those reported by Díaz et al. (2013) for *Atriplex* grown in saline soils of the SJV. In addition, *S. soda* was able to tolerate high levels of salinity (EC $\geq$ 10 dS m^{-1}) and it showed increases in fresh and dry weight with increased soil EC, indicating that salinity improved plant growth.

In *Atriplex* and *Halimione* species, salinity tolerance is related to specific mechanisms by which the plant can localize salts in specialized compartments (i.e., trichomes on the leaves) or excrete salts outside the plant tissues (i.e., onto the leaf surface). In general, in succulent-like halophytes species such as *Salicornia*, *Salsola*, and *Suaeda*, salts are accumulated in the vacuoles. For example, vacuoles occupy more than 70% of the leaf mesophyll cells in *Suaeda maritima*, which has the ability to store salts at concentrations higher than 500 mM (Hajibagheri et al., 1984).

S. soda did not show any symptoms of B toxicity when grown on saline soil (T1 and T2) containing >10 mg L^{-1} water extractable B. The concentration of B in the shoots showed a strong correlation with the water extractable B in soil at harvest with a Pearson correlation coefficient of $r = 0.91$ ($P \leq 0.05$). The plant B levels reported here are comparable to those reported by Díaz et al. (2013) and Watson et al. (1994) for *D. spicata* and *Atriplex* species grown under field conditions in the SJV and irrigated with saline drainage water for 4–6 years. In this study, the plants grown on saline soil (T1 and T2) accumulated 100 mg B kg^{-1} DW in only 4 weeks (Fig. 5), indicating that *S. soda* could be useful for phyto-management of B in soil and water, as described in Tassi et al. (2011).

Excessive levels of B (i.e. >4 mg L^{-1}) in soils can cause substantial losses in crop productivity (Maas, 1990). Leaching B out of the soil profile is sometimes used as a strategy to remediate excessive soluble B in soils but this method is unpractical in arid and semi-arid regions, especially because there is little water available. Importantly, leaching B from soils requires almost three times more water than that needed to leach salinity (Oster and Rhoades, 1975). Using salt and B-tolerant plants to help manage high soluble B levels in soil and water should be considered as a management tool for high saline and B soils. Uptake of B by *S. soda* in our study was about half the amount taken up by the B tolerant species *Puccinellia distans* that accumulated about ~1 mg B in plant shoot when exposed to 10 mg B L^{-1} in solution (Stiles et al., 2010). However, in the latter study *P. distans* was grown hydroponically and B was supplied for 6 weeks as part of saline solution, thus eliminating the chemical and biological complexity of B interactions with the soil. In our experiment, *S. soda* was able to take up significant amounts of B in 30 days.

S. soda accumulated about 3–4 mg Se kg^{-1} when grown on saline soil (T1 and T2) (Fig. 6) and 0.5 mg kg^{-1} when grown on control soil irrigated with 0.25 mg kg^{-1} Se in the saline solution (Fig. 6). There was a correlation between concentration of Se in shoot and water extractable Se in soil with a Pearson correlation coefficient of $r = 0.91$ ($P \leq 0.05$). Hence, it appears that *S. soda* is a moderate Se accumulator species and its harvested plant parts could be considered as a Se-enriched vegetable. In this regard, selenium is an essential micronutrient for humans and the consumption of Se-enriched 'agretti' could be integrated for use of an additional source of Se in Se deficient regions around the world (White and Broadley, 2009).

Currently, phyto-management strategies for soluble Se and B in the west side of central California rely on the use of moderately tolerant plant species such as Indian mustard (*B. juncea* L.) and canola (*B. napus* L.). However, the concentration of Se found in *S. soda* after exposure to Se-laden soil for only 30 days under greenhouse conditions is similar and even higher than other

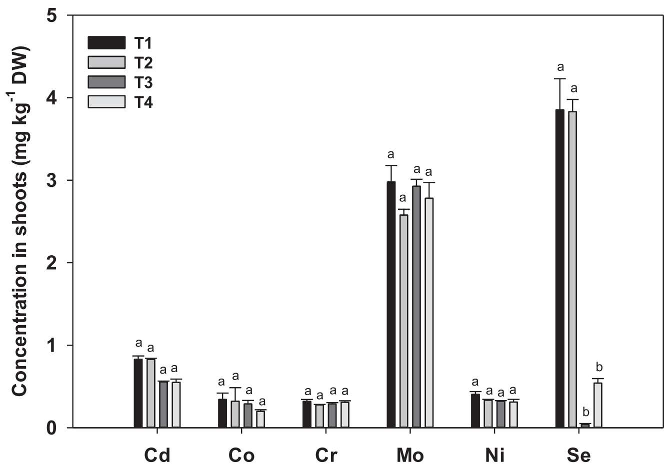

Fig. 6. Concentration of Cd, Co, Cr, Mo, Niand Se in *S. soda* shoot at harvest after 30 days from transplanting. Values represent average of 5 replicates and error bars represent SE. Similar letters indicate no significant ($P \leq 0.05$) difference between treatments for each element listed. (T1: soil with EC of 10 dS m^{-1}, T2: soil with EC 10 dS m^{-1} + saline solution, T3: control soil, and T4: control soil + saline solution, see Table 1). Levels of As and Pb were insignificant and too low to report.

species, as reported by Bañuelos (1996). Therefore, *S. soda* should be further evaluated for its ability to accumulate Se in field soils under various environmental conditions.

Some authors have proposed the use of halophytes for phytostabilization and phytoextraction of heavy metal contaminated saline soils (Wang et al., 2014; Manousaki and Kalogerakis, 2011). Although the evaluation of *S. soda* as a potential halophyte for phytostabilization of metal contaminated saline soil was not the goal of this study, we evaluated its potential impact on the uptake of micro-nutrients and trace elements, because 'agretti' will be considered as a new food crop. In *S. soda*, iron concentrations remained in the range of adequate for normal metabolic activities for halophytes such as *Atriplex* species (Lefèvre et al., 2009) and the uptake of Fe was significantly higher in the saline soil irrigated with good quality water (T1) compared to the same saline soil irrigated with the saline solution (T2) (Fig. 5). Uptake of S (Fig. 4), Cu (Fig. 5), Cd, Co, Cr, Mo, and Ni (Fig. 6) were similar among all treatments, while the uptake of Mn and Zn (Fig. 5) were significantly higher in plants grown on control soil (T3 and T4) relative to saline soil (T1 and T2). *S. soda* was able to take up trace elements at higher concentrations when their availability was higher in the soil solution (Table 3). These observations indicate that *S. soda* can absorb soluble metals, if present in the growing soil solution, but the plant might limit the shoot-to-root translocation, thus behaving more like an excluder rather than an accumulator (Baker, 1981). Milić et al. (2012) evaluated the ability of various halophyte species to absorb different heavy metals from inland and maritime saline areas and amongst the various halophyte studied, *S. soda* showed the lowest transfer factor ($[metal]_{shoot}/[metal]_{soil}$) for all investigated metals (Co, Cr, Cu, Fe, Mn, Ni, and Zn). Mendez and Maier (2008) describe in their review on the phytostabilization of metal in arid and semi-arid environments that it is important to use drought- and salt-tolerant plant species that are metal tolerant and do not accumulate (>1% dry biomass) metals in the above-ground biomass. Otherwise, 'agretti' might be a source of metal exposure to foraging animals, wildlife, and even humans. According to our results, *S. soda* could be a potential plant species to be used in phytostabilization projects and further studies are needed to elucidate its potential in soils with high concentration of bioavailable trace metals under saline conditions.

4. Conclusion

With the rapid spread of salinity and water shortage exacerbated by climate changes, cultivation of drought-tolerant and salt accumulator plants can help address food security challenges and the increasing demand for resource efficient agricultural products. In our study we showed that *S. soda* safely tolerates the saline (soil EC > 10 dS m^{-1}) and B-laden (10 mg L^{-1}) soils of the west side of central California and it can accumulate high concentrations of Na, B, and Se without showing any toxicity symptoms. Therefore, *S. soda* showed promising potential as an alternative crop or vegetable, and as management plant for excessive soluble Na, B, and Se in soil. The plant species should be further evaluated for its ability to accumulate soluble B and Se in other regions of the western United States.

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