CHILEAN JAR

Atriplex nummularia Lindl. as alternative for improving salt-affected soils conditions in semiarid environments: a field experiment

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ABSTRACT

Atriplex nummularia Lindl. represents a cost-effective alternative for improving salt-affected soils in arid and semiarid environments due to its high adaptability to salinity and water deficiency. This study aimed to investigate soil physical-chemical changes in response to *A. nummularia* cultivation under field condition. Additionally, we quantified its biomass yield and phytoextraction potential. Two treatments were evaluated: soil cultivated with Atriplex under two crop densities (1 × 1 and 2 × 2 m), and a control (bared soil) with four replicates. The samples were taken at three soil depths (0-5, 15-20, and 40-45 cm). In general, dry biomass yield for leaves, stems and roots, as well as the bulk density and the hydraulic conductivity of the soil were sensitive to crop densities. Thus, the use of *A. nummularia* can be recommended for phytoremediation of salt-affected soils, as well as to improve soil physical condition. When it comes to salt phytoextraction per area, we recommend planting *A. nummularia* at a 1 × 1 m crop density. The greater accumulation of salts was observed in leaves, as observed for Na (82% roughly). However, in order to improve soil physical conditions, we suggest the management of *A. nummularia* under 2 × 2 m crop density. Pruning was fundamental to increase the biomass yield and, consequently, the phytoextraction of specific ions, e.g., Na, Cl. It was responsible for 83% and 88% of the total dry biomass at 1 × 1 and 2 × 2 m crop density, respectively.

Key words: Halophytes, phytoextraction, phytoremediation, soil salinity, soil sodicity.

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INTRODUCTION

Soil physical-chemical degradation has been triggered by the presence of high salt levels in soils from arid and semiarid regions, which in turn has jeopardized agricultural productivity and environmental sustainability (Manousaki and Kalogerakis, 2011; Cao et al., 2012; Belkheiri and Mulas, 2013; Souza et al., 2014). Both kind of degradation negatively affect water and air movement on soils (Souza et al., 2011), crop development and production (Qadir et al., 2007). Soil salinization has also triggered desertification (Montanarella, 2007), affecting 1 to 3 million hectares (primarily cropland) concentrated in the Mediterranean countries (European Soil Bureau, 2014).

The use of salt-affected soils, valuable natural resources in arid and semiarid regions, has been increasing in areas where considerable investments were undertaken with regard to the irrigation system. Thus, adequate management of salt-affected soils is a challenge for global food security (Bennett et al., 2009). Among the management possibilities, the use of halophytes – plants that can survive in harsh environment conditions where the salt concentration exceeds 200 mmol L^{-1} NaCl (~ 20 dS m^{-1}), and 99% of other species cannot survive (Flowers and Colmer, 2008) – seems to be an affordable solution to reduce the high salt concentrations (Manousaki and Kalogerakis, 2011; Melo et al., 2016). This technique has been indicated as a new, noninvasive and low-cost technology for remediation of contaminated sites (Revathi et al., 2011).

Atriplex nummularia Lindl. fits this profile due to its high biomass yield and great ability to Na^+ and Cl^- uptake (Munns and Tester, 2008; Belkheiri and Mulas, 2013; Melo et al., 2016), as a result of its high capacity to accumulate salt within cells and eliminate them through specialized vesicles located on leaf surface (Freire et al., 2010). Overall, this tolerance is explained by the following major aspects: 1) Control of the salt uptake, often considered the most important; 2) xylem loading – K preferably; 3) removal of salts from xylem in the upper part of the roots, stems, petioles or leaves; 4) translocation of ions (Na^+ and Cl^-) and 5) promote Na^+ and Cl^- excretion by salt glands (modified trichomes) or bladders (modified epidermal cells), with tissue tolerance to Na^+ and Cl^- accumulation (Munns and Tester, 2008). In this context, *A. nummularia* stands out among the halophytes as an important species to recover sodic or saline-sodic soils (Shelef et al., 2012).

Data about Atriplex adaptability under high salinity levels has been easily found (Belkheiri and Mulas, 2013; Souza et al., 2014); however, studies regarding the adequate crop density for reclaiming

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salt-affected soils are scarce (Souza et al., 2014). Therefore, our study was carried out to evaluate soil physical-chemical changes in response to *Atriplex nummularia* cultivation under different crop densities, soil depths and periodic cutting system. Additionally, we quantified its biomass yield and phytoextraction potential.

MATERIALS AND METHODS

Study area and experimental set-up

The study area is located at Serra Talhada municipality, Pernambuco State (7°58’54”-8º01’36” S, 38º18’24”-38º21’21” W), semiarid region of northeast Brazil (Figure 1). Climate of the area is Bsw’h’ type, according to Köppen classification; rainy season extends from summer to autumn. During the study period, monthly rainfall was (mm): 88.1 (10 Feb), 25 (10 mar), 170.2 (10 Apr), 11.4 (10 May), 51 (10 June), 19.1 (10 July), 1.1 (10 Aug), 1.3 (10 Sept), 96.4 (10 Oct), 0.0 (10 Nov), 44.7 (10 Dec), 136.9 (11 Jan), 251.5 (11 Feb) (IPA, 2011). Annual average air temperature is approximately 27 °C. The soil from study region was classified as Inceptisols (USDA, 2006).

The field study was conducted in 2010-2011 in an uncultivated area because it has high salt concentration. In the past, there were beans, corn, and other irrigated plants. The experimental design was randomized blocks, factorial arrangement (3 × 3) with four replicates. Treatments comprised two crop densities (1 × 1 and 2 × 2 m), and a control (bare soil) and three soil depths (0-5, 15-20, and 40-45 cm).

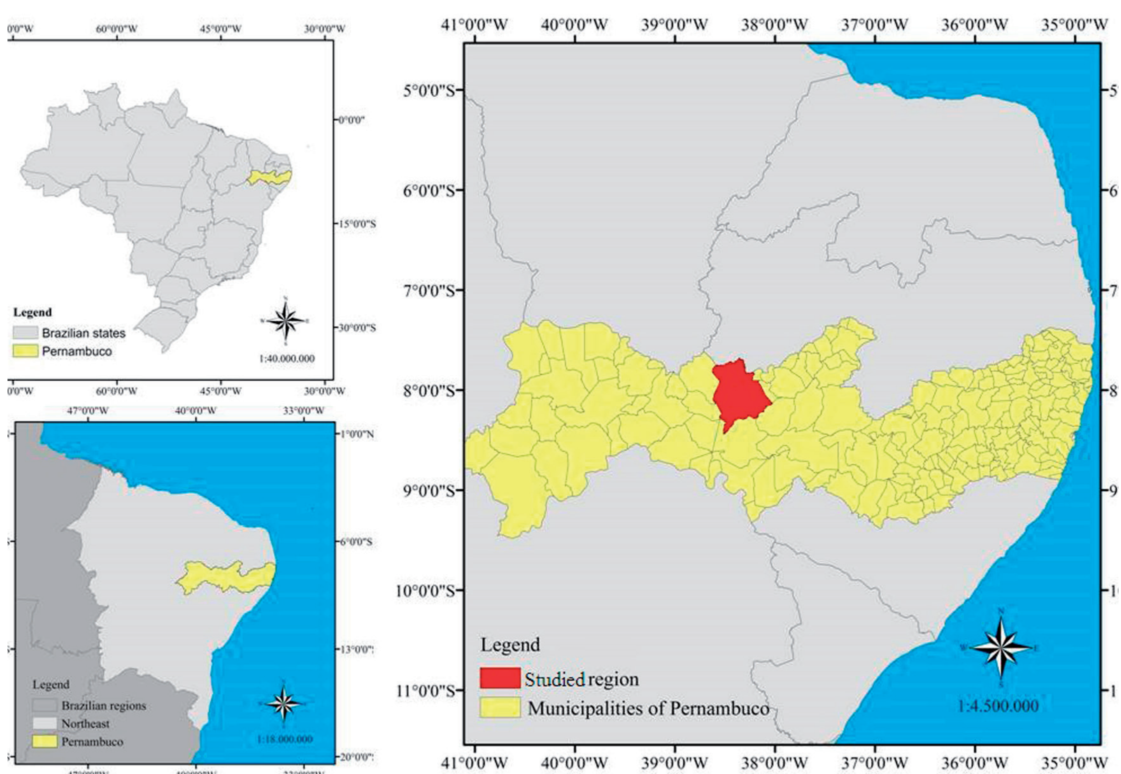
Atriplex nummularia seedlings were produced by cuttings of a single mother plant to preserve the genetic uniformity. It was cropped with 90-d-old and about 30 cm height (Souza et al., 2012). The transplant was done manually, with one plant per hole, without fertilizer application. A weekly irrigation was performed during the first 30 d for the establishment of seedlings.

The crop densities 1 × 1 and 2 × 2 m were composed by 36 and 9 plants, respectively, being considered as useful plot the four central plants of the 1 × 1 m crop density and one central plant of the 2 × 2 m crop density. All plants were pruned after 6 and 12-mo, removing all plant parts above 50 cm height, aiming to accelerate the salt extraction, as well as to remove the salts accumulated in shoots from the system. Canopy overlapping was not observed owing to pruning. After each pruning, leaf, stem and root were placed in an oven with forced circulation at 65 ºC. This step allowed for reaching weight stabilization and obtaining dry mass for measurement and subsequent analysis.

Sampling and chemical analyses

Core samples were collected at 50 cm from the stem and sieved through a 2 mm mesh. The following chemical analyses were made on soil samples: pH H_2O (1:2.5), exchangeable cations Ca^{2+}, Mg^{2+}, Na^+ and K^+, extracted using 1 M ammonium acetate (Thomas, 1982), Ca^+ and Mg^+ (atomic absorption spectrophotometry), Na^+ and K^+ (emission photometry flame), exchangeable Na^+ percentage (ESP) and Na^+ adsorption ratio (SAR) (USSL Staff, 1954), cation exchange capacity (Chapman, 1965), total organic C (Yeomans and

Figure 1. Geographical location of the experimental area.



Bremner, 1988). Those for physical analyses were: particle size characterization (hydrometer method), bulk density (volumetric ring method), particle density (volumetric flask method), hydraulic conductivity (decreasing and load constant method), total porosity, macro and microporosity (using the tension table), and resistance penetration (bench penetrometer) (Embrapa, 2011).

The saturation extract was obtained through the preparation of the soil saturation past, and extracted by vacuum. We measured its electrical conductivity (EC), pH, and soluble cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and anions (Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-) in soil past extract. It was also calculated the sodium adsorption ratio ($SAR = Na^+/[(Ca^{2+} + Mg^{2+})/2]^{0.5}$) (USSL Staff, 1954). The dry mass obtained from leaf, stem and root fractions was ground in a Willey grinder. Nitric-perchloric acid digestion (Silva, 2009) was conducted then. Sodium and K contents were determined by flame emission photometry. Chlorides were determined according to Malavolta et al. (1997).

Statistical analysis

Results were analyzed by ANOVA and means were compared by Tukey's test ($p < 0.05$) using Statistical Analysis System software (SAS Institute, Cary, North Carolina, USA). Non-normal distributed variables, such as penetration resistance and hydraulic conductivity were transformed to log 10 aiming to address the ANOVA assumptions. Such an analysis was chosen because it is one of the most useful techniques to assess the differences among group or variable means.

RESULTS AND DISCUSSION

Biomass yield and phytoextraction of salts

Biomass yield per plant was higher under 2 × 2 m crop density (Table 1). Such finding was supported by the lower water, light, and nutrients competition between plants. Pruning was efficient to stimulate biomass yield, being responsible for 83% and 88% of total dry biomass at 1 × 1 and 2 × 2 m crop density, respectively. Souza et al. (2014), studying Atriplex biomass yield under field condition, observed that 97% of the total biomass was derived after pruning.

The highest Na and Cl contents per plant were observed at 2 × 2 m density due to the reduced competition among plants, while the phytoextraction of salts per area was greater at 1 × 1 m crop density (i.e. 10 000 plants ha^{-1}) (Table 2). The biomass yield was responsible for changes on phytoextraction not only per plant but also per area. Leaf Na concentrations of nearly 15% indicate the efficiency of this species for phytoremediation of highly saline and sodic soils, generally encountered in semiarid environments.

Proportionally, the greater accumulation of salts was observed in leaves, as observed for Na (82% roughly). Such storage was likely due to the presence of small vesicles found in the epidermis of plants (Freire et al., 2010). Halophytes are able to provide osmotic adjustment through the uptake and accumulation of the salts in leaves – a tolerance mechanism in response to high salinity levels (Araújo et al., 2006). This process takes place with cellular compartmentalization of salt ions into vacuoles, decreasing osmotic potential of the cytoplasm; hence, keeping metabolism balance and enzymatic functions (Dias and Blanco, 2010). These structures are enriched in salts which in turn decrease Na

Table 2. Concentration, content, and extraction of Na^+ and Cl^- in leaf, stem and shoot of *Atriplex nummularia* under 1 × 1 and 2 × 2 m crop densities.

Element		Treatment density	Concentration	Content	Extraction
			%	g plant^{-1}	kg ha^{-1}
Na^+	Leaf	1 × 1	14.35A	35.83B	358.29A
		2 × 2	14.98A	112.14A	280.34B
	Stem	1 × 1	1.73A	3.77B	37.71A
		2 × 2	2.03A	4.42A	44.23A
	Shoot	1 × 1	-	33.12B	396.00A
		2 × 2	-	116.56A	324.57B
Cl^-	Leaf	1 × 1	11.90A	29.70B	297.08A
		2 × 2	12.21A	82.81A	207.03B
	Stem	1 × 1	2.95A	2.52B	25.25A
		2 × 2	2.37A	10.91A	27.27A
	Shoot	1 × 1	-	32.22B	322.33A
		2 × 2	-	93.72A	234.30B

Means followed by the same letter do not differ significantly according to Tukey test ($p < 0.05$) between crop densities.

Table 1. Fresh and dry matter yield of leaves, stems and total yield of *Atriplex nummularia* subjected to successive pruning at different crop densities.

Density treatment		Fresh matter			Dry matter		
		Leaf	Stem	Total	Leaf	Stem	Total
		kg plant^{-1}					
1 × 1	1st Pruning	0.30Bb	0.11Bb	0.41Bb	0.07Bb	0.05Ab	0.13Bb
	2nd Pruning	1.32Ba	0.75Ba	2.07Ba	0.28Ba	0.35Bab	0.64Ba
	Total	1.62	0.86	2.48	0.35	0.4	0.77
2 × 2	1st Pruning	0.62Ab	0.16Ab	0.78Ab	0.14Ab	0.08Ab	0.22Ab
	2nd Pruning	3.15Aa	1.65Aa	4.80Aa	0.75Aa	0.88Aab	1.63Aab
	Total	3.77	1.81	5.58	0.89	0.96	1.85

Means followed by the same capital letters do not differ significantly according to Tukey test ($p < 0.05$) between treatments. Means followed by the same lower-case letters do not differ significantly according to Tukey test ($P < 0.05$) in function of pruning applied.

and Cl concentrations in order to maintain water uptake in saline soils (Türkan and Demiral, 2009; Souza et al., 2012).

Physical-chemical soil changes

The high salinity concentration on soil surface is consequence of natural encountered conditions observed in semiarid regions (i.e. evapotranspiration higher than rainfall); however, this situation has been also boosted by mismanaged irrigation and poor water quality use. An increase in cation-exchange capacity (CEC) is shown in depth, generating the highest accumulation of salts (Table 3); also the highest Na^+ concentrations in soil solution at 15-20 and 40-45 cm depth were responsible for the highest EC values.

Sodium accumulation in subsurface provoked a series of damages on physical properties, for example: particles dispersion and reduction in soil porosity (Table 4). As a result, not only did we observe an increase in the penetration resistance but also air movement decreased. These effects were associated to high silt (374 g kg^{-1}) content, which induced for porosity obstruction (mainly macroporosity). Both dispersion and eluviation of the soil fine fraction have triggered soil sealing in semiarid environments (Spera et al., 2008; Ribeiro et al., 2009; Santos et al., 2010). The lack of change in particle density values was chiefly because this soil parameter is not influenced by soil management.

The large dispersion shown by the variation coefficient for physical and chemical variables (Tables 3 and 4) may be associated with the soil formation process encountered in Inceptisols – alluvial sedimentation during the hydrogeological development in different times – explaining the variations in their constitution. High heterogeneity on physical-chemical parameters was also observed in other saline soils (Queiroz et al., 2010; Santos et al., 2010). Salinization process also contributes to soil heterogeneity, promoting colloids movement and changing soil properties in small distances (Ribeiro et al., 2009).

Table 3. Chemical properties of Inceptisols in function of sampling depth.

Depth	EC	Na^+	CEC	K^+	Na^+
cm	dS m^{-1}	—— $cmol_c$ kg^{-1}	——	—— $mmol_c$ L^{-1}	——
0-5	26.90B	2.64B	6.58B	10.57B	413.53B
15-20	40.86A	4.83A	9.20A	17.81A	696.43A
40-45	34.53A	6.79A	8.12A	13.65A	534.05A
CV, %	33.21	60.08	13.98	42.64	42.64

Means followed by the same letter in columns do not differ significantly according to Tukey test ($p < 0.05$) between depths.
EC: Electrical conductivity, CEC: cation exchange capacity (exchangeable Na^+ and K^+ were transformed to log 10).

Table 4. Physical properties of Inceptisol in function of different depths.

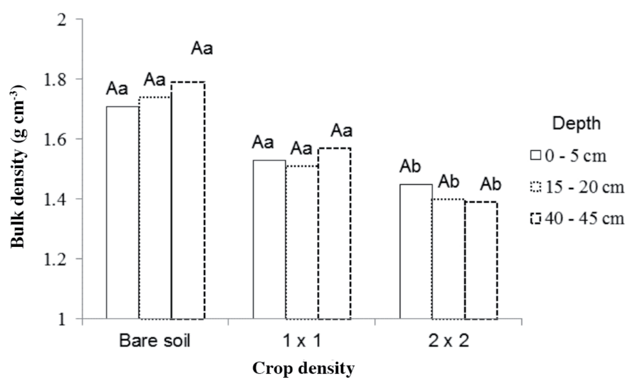
Depth	PR	PD	Ksat	P
cm	MPa	g cm^{-3}	cm h^{-1}	%
0-5	0.19A	2.48A	0.7A	19.75A
15-20	0.34A	2.38A	1.4A	16.47B
40-45	0.41B	2.34A	1.8A	15.72B
CV, %	51.16	4.13	42.15	15.36

Means followed by the same letter in columns do not differ significantly according to Tukey test ($p < 0.05$) between depths.
PR: Penetration resistance, PD: particle density, Ksat: hydraulic conductivity (PR and Ksat were transformed to log 10), P: total porosity.

Atriplex nummularia effects on soil physical properties

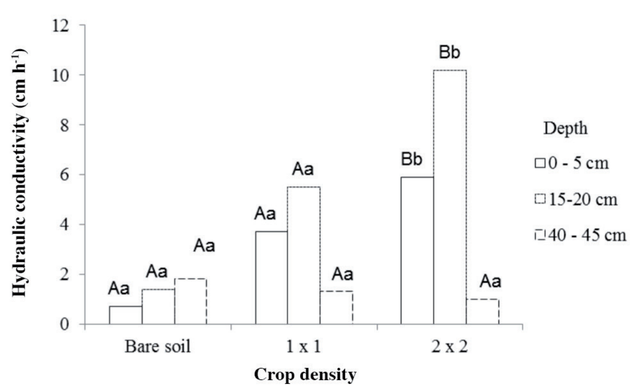
At 2 × 2 m crop density, reduction in bulk density (Figure 2) and increase in hydraulic conductivity (Figure 3) were observed. These observations demonstrate the effect that Atriplex exerts on improving the physical conditions of the studied soil; however, this reduction was not observed under 1 × 1 m crop density. Root development improved the soil physical quality given the formation of biopores that leads to an increase in both macropores and water infiltration rate. The influence of plant root system in depth is related to the lack of water on soil surface in semiarid environments, thus, this halophyte shows a high capacity to explore deeper layers of soil to supply their water requirements (Norman et al.,

Figure 2. Bulk density in response to different soil depths and crop density.



Means followed by same capital letters do not differ significantly according to Tukey test ($p < 0.05$) between depths. Means followed by same lower-case letters do not differ significantly according to Tukey test ($p < 0.05$) between crop densities.

Figure 3. Hydraulic conductivity in response to different soil depths and crop density.



Means followed by same capital letters do not differ significantly according to Tukey test ($p < 0.05$) between depths. Means followed by same lower-case letters do not differ significantly according to Tukey test ($p < 0.05$) between crop densities.

2010), interfering in subsurface soil structure (Qadir et al., 2007; Leal et al., 2008). The highest bulk density values observed for bare soils are related to the lack of vegetation cover on the soil surface, which trigger the sealing and its detachment due to the action of raindrops on soil particles that transfer kinetic energy to soil surface in the form of pressure force (Foltz et al., 2009). In addition, the bare soil showed bulk density values higher than 1.4 g cm^{-3}, critical threshold according to Michelon et al. (2009) that indicate soil compaction.

Additionally, plants canopy promotes shadow on soil minimizing evaporation from surface, root system releases organic substances increasing biological activity, and plants uptake elements from different depths in soil altering physic-chemical balance. Vegetation establishment may improve soil quality, especially halophyte plants in salt affected soils, changing degraded areas in soils adequate for cultivation. It is fundamental spread plants on unprotected soils, notably in arid and semiarid regions.

CONCLUSIONS

The use of *Atriplex nummularia* can be recommended for phytoremediation of salt-affected soils, as well as to improve soil physical condition. In general, dry biomass yield for leaves, stems and roots, as well as bulk density and hydraulic conductivity of soil were sensitive to crop densities. When it comes to salt phytoextraction per area, we recommend planting *A. nummularia* at a 1 × 1 m crop density. The greater accumulation of salts was observed in leaves, as observed for Na (82% roughly). However, in order to improve soil physical conditions, we suggest the management of *A. nummularia* under 2 × 2 m crop density. Pruning was fundamental to increase the biomass yield and, consequently, the phytoextraction of specific ions, e.g., Na, Cl. It was responsible for 83% and 88% of the total dry biomass at 1 × 1 and 2 × 2 m crop density, respectively.

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