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Maman Nassirou Ado, Didier Michot, Y. Guero, Vincent Hallaire, N. Dan Lamso, et al.. Echinochloa stagnina improves soil structure and phytodesalinization of irrigated saline sodic Vertisols. *Plant and Soil*, 2019, 434 (1-2), pp.413-424. <10.1007/s11104-018-3853-9>. <hal-02083278>

HAL Id: hal-02083278

<https://hal.science/hal-02083278v1>

Submitted on 29 Mar 2026

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Echinochloa stagnina improves soil structure and phytodesalinization of irrigated saline sodic Vertisols

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Received: 11 December 2017 / Accepted: 15 October 2018
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Abstract

Aim This study tested the capacity of the semi-aquatic grass *Echinochloa stagnina* to grow on highly salt-affected soil to improve soil structure and decrease salinity of saline Vertisols.

Methods The experimental study, conducted over 11 months on soil columns in laboratory conditions, tested three treatments: i) ponded bare soil without crops (CT), ii) soil cultivated with *E. stagnina* (CEs) in two successive cropping seasons and (iii) soil permanently cultivated with *E. stagnina* (CEp) with a staggered harvest.

Results Soil porosity increased when cultivated with *E. stagnina* but remained constant under bare soil. At the end of the experiment, soil cultivated with *E. stagnina* had higher macroporosity (6–9%) than bare soil (3–4%), linked mainly to root development. Moreover, salt stock, which was initially similar in the columns, decreased by 65–87% in soil cultivated with *E. stagnina* and by 34–45% in ponded bare soil. Salt accumulation in plant biomass contributed 22–35% of

soil desalinization vs 65–78% due to leaching. In addition, *E. stagnina* produced 10–12 t.ha⁻¹ (dry weight) of forage in 11 months, which makes it of economic interest for farmers.

Conclusions An irrigated *E. stagnina* crop appears effective at improving physical properties and reducing salinity of Vertisols and also at producing forage. Future studies must be performed with modeling approaches that use hydrodynamic parameters to characterize phytodesalinization of Vertisols by *E. stagnina*.

Keywords Vertisols · Soil salinity · Soil structure · Phytodesalinization

Introduction

Soil salinity is a crucial constraint of irrigated land to achieving sustainable development, particularly in arid and semi-arid zones, due to water scarcity and high evaporation rates (Marlet 2005; Nouri et al. 2017). Irrigated vertic soils are particularly exposed to soil salinization because of their low saturated hydraulic conductivity, which inhibits salt leaching (Adam et al. 2012). In Niger, irrigated rice production accelerates soil salinization in the Niger River valley, causing agricultural land to be abandoned (Guéro 2000; Adam 2011).

Different engineering-based remediation techniques have been developed to decrease soil salinity, including physical remediation, chemical remediation and phytoremediation (Singh and Ward 2004; Qadir et al. 2007; Gharaibeh et al. 2014; Nouri et al. 2017).

Responsible Editor: Wieland Fricke.

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s11104-018-3853-9>) contains supplementary material, which is available to authorized users.

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Phytodesalinization is a biological approach using salt-tolerant plants or halophytes to decrease soil salinity and improve crop production (Qadir et al. 2000; Ravindran et al. 2007; Zorrig et al. 2012; Jesus et al. 2015). This approach is increasingly investigated since conventional approaches are difficult to apply in water-limited areas and are less effective in fine-textured soils (Adam et al. 2012). Plants used for phytodesalinization generally have strong root systems to improve soil structure and increase salt leaching (Akhter et al. 2004; Blanchart et al. 2004) or have a high capacity to accumulate salt in their biomass (Zorrig et al. 2012; Zhao et al. 2013).

The high phytodesalinization potential of *Echinochloa stagnina* has been reported by several authors in the Niger River valley as being able to reduce soil alkalinity by 50–60% in alkaline silty soils after one year of growth (Barbiero et al. 2001) or to decrease salt stock by 72–81% of saline Vertisols after 8 months of growth (Ado et al. 2016). Most studies of soil salinity reclamation argued that increased salt leaching was the main process of phytodesalinization (Barbiero et al. 2001; Qadir et al. 2007); however, the influence of plant-root modification of soil structure in decreasing soil salinity has not been demonstrated, particularly in Vertisols. Indeed, Vertisols have low hydraulic conductivity when saturated, and their high clay content may limit plant root development. The aim of this study was to test *E. stagnina*'s capacity to improve structure and decrease salinity of a saline sodic Vertisols compared to a ponded bare soil. The study was conducted on soil columns under controlled conditions in the laboratory.

Materials and methods

Soil characteristics

The study was conducted on soil columns (16 cm in diameter × 25 cm high), collected from the topsoil layer (0–25 cm) in irrigated paddy fields of Kollo (13° 16' 35.32" N, 2° 21' 31.81" E), located in the Niger River valley 50 km southeast of Niamey (Niger). The soil is classified as an *acid saline sodic Vertisol* (Adam 2011; FAO 2014) with high clay content (69.4%), low pH (4.5–5.0), high EC of soil saturated paste (15 dS.m⁻¹) and very low saturated hydraulic conductivity (1.5–2.8 × 10⁻⁸ m.s⁻¹) (Adam et al. 2012; Ado et al. 2016).

The columns were filled with two layers: i) a reconstituted topsoil layer (0–19 cm deep) with a

mixture of sieved small (< 1 cm diameter) aggregates, slightly compacted to obtain a dry bulk density of 1.4 g.cm⁻³; and ii) an undisturbed soil layer (19–25 cm deep) that conserved the initial soil structure. This two-layer organization aimed to simulate the vertical variability in soil structure in a puddled soil layer (i.e. plowed when saturated), as observed in the paddy fields. The reconstituted topsoil layer was prepared from a uniform mixture of the material from all columns to limit variability in soil salinity among treatments at the beginning of experiment.

Experimental design

The experimental design was based on comparing three treatments (three replicates each): i) ponded bare soil without a crop (CT), ii) soil cultivated with *E. stagnina* (CEs) in two successive cropping seasons separated by a total harvest and (iii) soil permanently cultivated with *E. stagnina* (CEp) subjected to a staggered harvest during the experiment. The experiment lasted 11 months (i.e. two 4.5-month cropping seasons separated by a 2-month inter-cropping period).

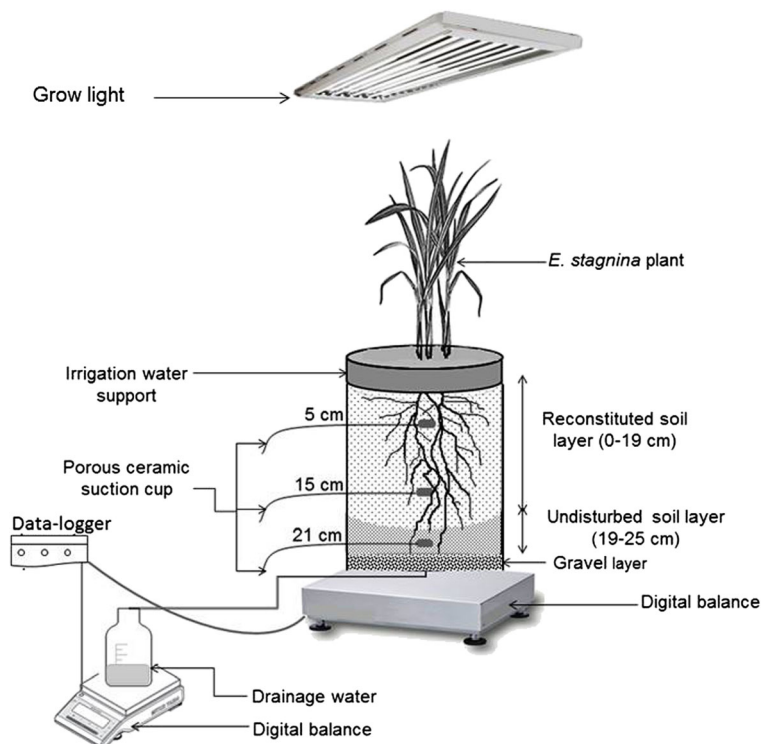
Soil structure and salinity were monitored by equipping two of the three replicates in each treatment with three porous ceramic suction cups each, installed at depths of 5, 15 and 21 cm, to extract soil solution (Fig. 1). The third replicate of each treatment was equipped mainly to collect drainage water at the bottom of the column and was dismantled at the end of the first cropping season to characterize soil structure, salinity and crop roots at that time. The mass of each column (including soil, plant, irrigation water and drainage water) was measured and recorded automatically every 10 min by digital balances connected to a data-logger (Fig. 1). The bottom of each column was set on a gravel layer to facilitate free drainage.

Crop production

At the beginning of the cropping season, three cuttings of *E. stagnina* (15–20 cm high) per column were transplanted to the previously water-saturated columns. Once they regenerated, plants were irrigated twice per week. At each irrigation date, the height of water above the soil surface was adjusted to 7 cm.

A mineral fertilizer (12–15–20 NPK) was applied twice per cropping season at a rate of 200 kg.ha⁻¹ one week after planting and 150 kg.ha⁻¹ one month after the

Fig. 1 Design of *Echinochloa stagnina* growth experiment for two of the three replicate columns of saline sodic Vertisol



first application. Aboveground crop biomass was harvested at the end of each cropping season to measure the yield of fresh and dry aboveground biomass of *E. stagnina* per column. The first harvest consisted of cutting all biomass on CE columns and most biomass (to a height of 10 cm) on CEP columns.

The inter-cropping period lasted 60 days without irrigation of CE and CT columns, but with irrigation of CEP columns, to regenerate the plants. Like for the first cropping season, the second cropping season was started by planting three cuttings per CE column. At the end of the second cropping season, all aboveground biomass was harvested from CE and CEP columns.

Characterization of soil structure

Soil bulk density was measured at the end of each cropping season and always when the soil was saturated to limit the bias caused by Vertisol shrinkage while drying. Undisturbed soil samples from the 0–8, 8–18 and 18–25 cm soil layers in each column were weighed when wet and, after drying in an oven for 48 h at 105 °C, when dry.

Soil macroporosity was measured at the end of the experiment by image analysis of undisturbed soil cores

(Lamandé et al. 2003; Bottinelli et al. 2014). Soil samples from the 0–8, 8–18 and 18–25 cm soil layers from the two instrumented columns of each treatment were dried at a constant temperature of 20 °C for 10 days after having been wrapped in plastic film on their sides to limit lateral cracking. Soil samples were weighed to monitor water loss during drying until a water content of 0.17 g.g⁻¹, close to that measured in the fields at the end of the inter-cropping period, was reached. After drying, samples were impregnated with a polyester resin containing fluorescent dye. Each soil sample was cut in the horizontal plane to produce a 5 mm thick polished section. Images of each polished section were captured under ultraviolet light with an Olympus LC20 digital camera and digitized in a rectangular grid of 1600 × 1200 pixels with a spatial resolution of 30 μm per pixel, allowing macropores to be identified (Bottinelli et al. 2014).

Macropore space was quantified from binary images using Visilog software (Thermo Fisher Scientific, Hillsboro, Oregon, USA) to derive (i) specific surface porosity, expressed as the percentage of total image pixels belonging to macropores, and (ii) pore typology according to pore shape and size. Macropore shape was expressed by the elongation index ($Is = [(perimeter)^2 / 4\pi \times area]$) to distinguish tubular macropores ($Is < 5$),

crack macropores ($5 \leq I_s \leq 15$) and packing macropores ($I_s > 15$) (Lamandé et al. 2003).

Soil salinity monitoring

Soil salinity (EC and salt stock) was measured at the beginning and end of each cropping season. At the beginning, one composite soil sample was collected from the reconstituted soil material of all columns, while another was collected from the undisturbed soil layer of each column. At the end of each cropping season, soil samples were collected from the 0–8, 8–18 and 18–25 cm soil layers in each column. EC from a 1:5 soil:water extract ($EC_{1:5}$) was measured for each soil sample according to ISO standard 11,265 (AFNOR 1996). The EC of the soil solution, collected every two weeks, was measured at 25 °C.

Salt stock (SS) was calculated for the three soil layers (0–8, 8–18 and 18–25 cm) according to Eqs. 1 and 2 (Adam et al. 2012). Equation 2 was obtained from linear regression of salt content of a soil sample as a function of $EC_{1:5}$, based on 36 samples collected from all soil columns ($R^2 = 0.96$).

$$SS = \left(\frac{TS}{M} \right) \times Da \times h \quad (1)$$

$$TS = 0.0437 \times CE_{1:5} - 0.0145 \quad (2)$$

with TS the mass of salt in the soil sample (g), M the soil sample mass (g), Da the soil bulk density ($g \cdot cm^{-3}$) and h the thickness of the soil layer (cm).

The amount of salt removed by drainage water (SD, g), collected weekly, was measured after evaporating the water in an oven.

At the end of each cropping season, Ca, Na, Mg, K, Cl, P and S contents were analyzed in aboveground and root biomass according to ISO/CEI standard 17,025 using i) inductively coupled plasma atomic emission spectroscopy for Ca, Mg, S and K and ii) atomic absorption spectrometry for the other elements. Salt content in aboveground (TS_b , $g \cdot kg^{-1}$) and root (TS_r , $g \cdot kg^{-1}$) biomass was estimated by summing Ca, Na, Mg, K, Cl, P and S contents, as performed by Zhao et al. (2013).

SS in the soil was calculated weekly based on the amounts of salt removed in drainage water, accumulated in plant biomass and input from irrigation water. Biomass ($biom$) dynamics in columns was estimated

from plant height (measured weekly), initial biomass ($biom_{init}$) and final biomass ($biom_{fin}$), according to a logistic model (Paine et al. 2012):

$$Biom(t) = \frac{biom_{fin}}{\left(biom_{init} + (biom_{fin} - biom_{init}) e^{-rt} \right)} \quad (3)$$

with r a growth rate estimated from monitoring plant height.

This logistic model was applied to each cropping season of each column using the “SSlogis” function of R software (Chessel and Dufour 2008; Pinheiro et al. 2009). Thus, the weekly salt stock in the soil was calculated recursively as:

$$SS_t = SS_{t-1} + SI_{t-1} - SD_{t-1} - SB_{t-1} \quad (4)$$

$t = 7 \text{ days}$

with SS_t the soil salt stock in week t , and SS_{t-1} , SI_{t-1} , SD_{t-1} and SB_{t-1} the amounts of salt in the soil, irrigation water, drainage water and plant biomass in week $t-1$, respectively.

Finally, salt balance (ΔSS) was derived from initial (SS_i) and final (SS_f) SS for the three soil layers (0–8, 8–18 and 18–25 cm) (Eq. 5). Positive values of ΔSS indicate salt removal and thus desalinization, while negative values of ΔSS indicate salt accumulation.

$$\Delta SS = SS_i - SS_f \quad (5)$$

Statistical analysis

Linear mixed models (LMM) were calculated (“lme4” package of R software) to assess changes in soil SS over time (from the initial state to the end of second cropping season) in columns of each treatment. LMM is a mathematical extension of classic linear models (Gaudart et al. 2010) that considers both fixed effects (α , β) linked to time and random effects linked to each treatment plot (α_i) to describe the relationship between a response variable y_{ij} and covariates x_{ij} in repeated-measurement data that are grouped according to cluster factor i :

$$Y_{i,j} = \alpha + (\alpha_i + \beta)x_{i,j} + \varepsilon_{i,j} \quad (6)$$

with ε_{ij} the real distribution of errors. The random effects (α_i) linked to the cluster factor follow normal distributions with zero mean and constant variance. Mixed models are recommended to reduce the bias of estimates based on repeated measurements, since random effects can capture correlations between observations (Zuur et al. 2009). Pearson correlations were also calculated

between the parameters to identify significant ($P < 0.05$) relationships between changes in soil salinity and soil structure or crop agronomic parameters.

Results

Crop production

Total dry weight biomass produced by permanent *E. stagnina* crops (columns CEp1 and CEp2) after 8 months of growth ranged from 11 to 12 t.ha⁻¹, slightly higher than the 10–11 t.ha⁻¹ yielded by seasonal *E. stagnina* (columns CEs1 and CEs2) (Online Resource 1). Production of aboveground *E. stagnina* biomass was greater at the end of the second cropping season (ES2) (6.6–8.2 t.ha⁻¹) than at the end of the first cropping season (ES1) (3.3–4.4 t.ha⁻¹) on all columns.

Similarly, dry root biomass of *E. stagnina* was greater at ES2 (1.1–3.1 t.ha⁻¹) than at ES1 (0.7 t.ha⁻¹) on all columns, particularly in the topsoil (0–8 cm) (Online Resource 1). At ES2, dry root biomass was again greater in columns with permanent *E. stagnina* than in those with seasonal *E. stagnina*. At ES2, root biomass represented 20–25% of total biomass in CEp1 and CEp2 and 14% of total biomass in CEs1 and CEs2.

Soil structure dynamics

Among columns, bulk density (BD) was initially the same in reconstituted soil layers (1.4 g.cm⁻³ at 0–8 and 8–18 cm) but different in undisturbed soil layers (1.42–1.59 g.cm⁻³ at 18–25 cm) (Table 1). At the end of each cropping season, the initial BD had decreased in 0–8 and 8–18 cm soil layers in all treatments, except in CT2 in the 8–18 cm soil layer, whose BD had remained constant. At ES2, the initial BD of the 0–8 and 8–18 cm soil layers had decreased by 10–20% in soil cultivated with *E. stagnina* (CEp and CEs) but remained constant in bare soil (CT). In the 18–25 cm soil layer, BD decreased in cultivated soil but increased in bare soil.

Total macroporosity at the end of experiment (ES2) was higher in cultivated soil (6–9% and 3–6% at 0–8 and 18–25 cm, respectively) than in bare soil in all soil layers (3–4% and < 1% at 0–8 and 18–25 cm, respectively) (Fig. 2). Tubular macropores were dominant except in soil cultivated with seasonal *E. stagnina* (CEs1 and CEs2) at 0–8 and 18–25 cm, in which packing macropores prevailed. The packing macropores,

linked to soil aggregation, were less common in bare soil in all soil layers but represented 2–5% of macropores in cultivated soil.

Soil salinity dynamics

The initial EC of soil solution ranged from 13 to 16 and 18–25 dS.m⁻¹ at depths of 5 and 21 cm, respectively (Fig. 3). The EC of soil solution decreased in all treatments over time. The decrease in soil EC was more marked after the inter-cropping period. At ES2, EC was lower in soil cultivated with *E. stagnina* (having decreased by 72–94% and 54–92% at 5 and 21 cm, respectively) than in bare soil (having decreased by 74% and 42% at 5 and 21 cm, respectively).

SS was initially similar in all columns, except in CEp1, which had a slightly higher SS (Fig. 4a, Online Resource 2). SS decreased over time in all columns, slowly during the first cropping season (by 5–14% in cultivated soil and 3% in bare soil) and more rapidly during the second cropping season after the inter-cropping period. During the second cropping season, the decrease in SS was greater in cultivated soil (CEp and CEs) than in bare soil (CT1 and CT2). At ES2, SS had decreased by 65–87% in soil cultivated with *E. stagnina* and by 34–45% in bare soil.

LMM confirmed that SS decreased significantly ($p < 0.001$) from its initial state to ES2 (Fig. 4b). At ES2, SS was significantly higher in bare soil (CT1 and CT2) than in cultivated soil (CEp and CEs). However, the difference in SS reduction between permanent and seasonal *E. stagnina* was not significant.

Salt removal by drainage water was small during the first cropping season but increased considerably during the second cropping season in all treatments after the inter-cropping period (Fig. 5). It represented 48–75% of the initial SS in soil cultivated with *E. stagnina* and 36–46% in bare soil. Salt content in plant biomass ranged from 121.0–150.3 g.kg⁻¹ in aboveground plant biomass and from 26.2–31.2 g.kg⁻¹ in root biomass at the end of both cropping seasons (Online Resource 3). Total salt accumulation in aboveground plant biomass over both cropping seasons (1456–1786 kg.ha⁻¹) represented 22–27% of the initial soil SS. Total salt accumulation in aboveground plant biomass was higher at ES2 (880–1320 kg.ha⁻¹) than at ES1 (440–660 kg.ha⁻¹). In soil cultivated with *E. stagnina*, the amount of salt removed by drainage water was 2–4 times as high as that accumulated in plant biomass.

Table 1 Bulk density ($\text{g}\cdot\text{cm}^{-3}$) of 0–8, 8–18 and 18–25 cm soil layers measured at different dates for each column of the three treatments. ES1 is the end of first cropping season; ES2 is the end of second cropping season. CEp1, CEp2 and CEp3 are columns

permanently cultivated with *Echinochloa stagnina*; CE1, CE2 and CE3 are columns cultivated with seasonal *E. stagnina*; CT1, CT2 and CT3 are columns with bare soil

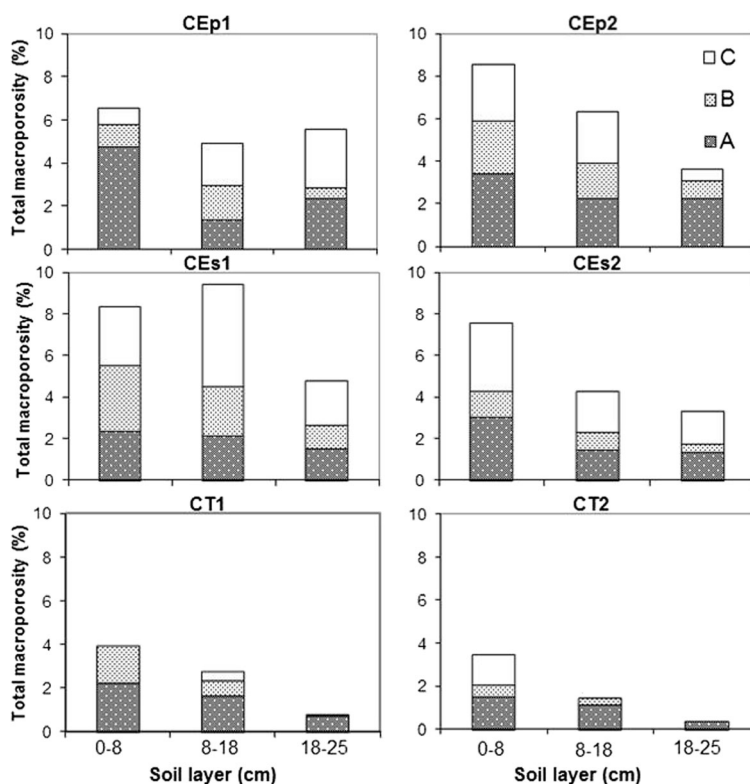
Date	Layer (cm)	<i>Permanent E. stagnina</i>			<i>Seasonal E. stagnina</i>			Bare soil		
		CEp1	CEp2	CEp3	CEs1	CEs2	CEs3	CT1	CT2	CT3
Initial	0–8	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
ES1				1.37			1.26			1.30
ES2		1.24	1.25		1.11	1.26		1.39	1.37	
Initial	8–18	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
ES1				1.30			1.37			1.34
ES2		1.22	1.27		1.27	1.23		1.38	1.41	
Initial	18–25	1.59	1.49	1.47	1.53	1.51	1.48	1.52	1.48	1.42
ES1				1.42			1.37			1.39
ES2		1.30	1.32		1.37	1.42		1.56	1.50	

Correlation between soil structure, soil salinity and plant characteristics

The correlation matrix (Table 2) showed a significant negative correlation between soil BD and soil

macroporosity ($r = -0.82$). Aboveground biomass and root biomass were positively correlated with soil macroporosity ($r = 0.73$ and 0.63 , respectively) and negatively correlated with SS ($r = -0.58$). Salt removal by drainage water was negatively and significantly

Fig. 2 Distribution at the end of the experiment of total macroporosity for each of the two instrumented soil columns in the 0–8, 8–18 and 18–25 cm layers. Treatments are columns cultivated with permanent *Echinochloa stagnina* (CEp1 and CEp2), columns cultivated with seasonal *E. stagnina* (CEs1 and CEs2) and bare soil columns (CT1 and CT2). Type A represents tubular macropores with an elongation index (Is) < 5, B represents cracks with an Is of 5–15 and C represents packing macropores with an Is > 15



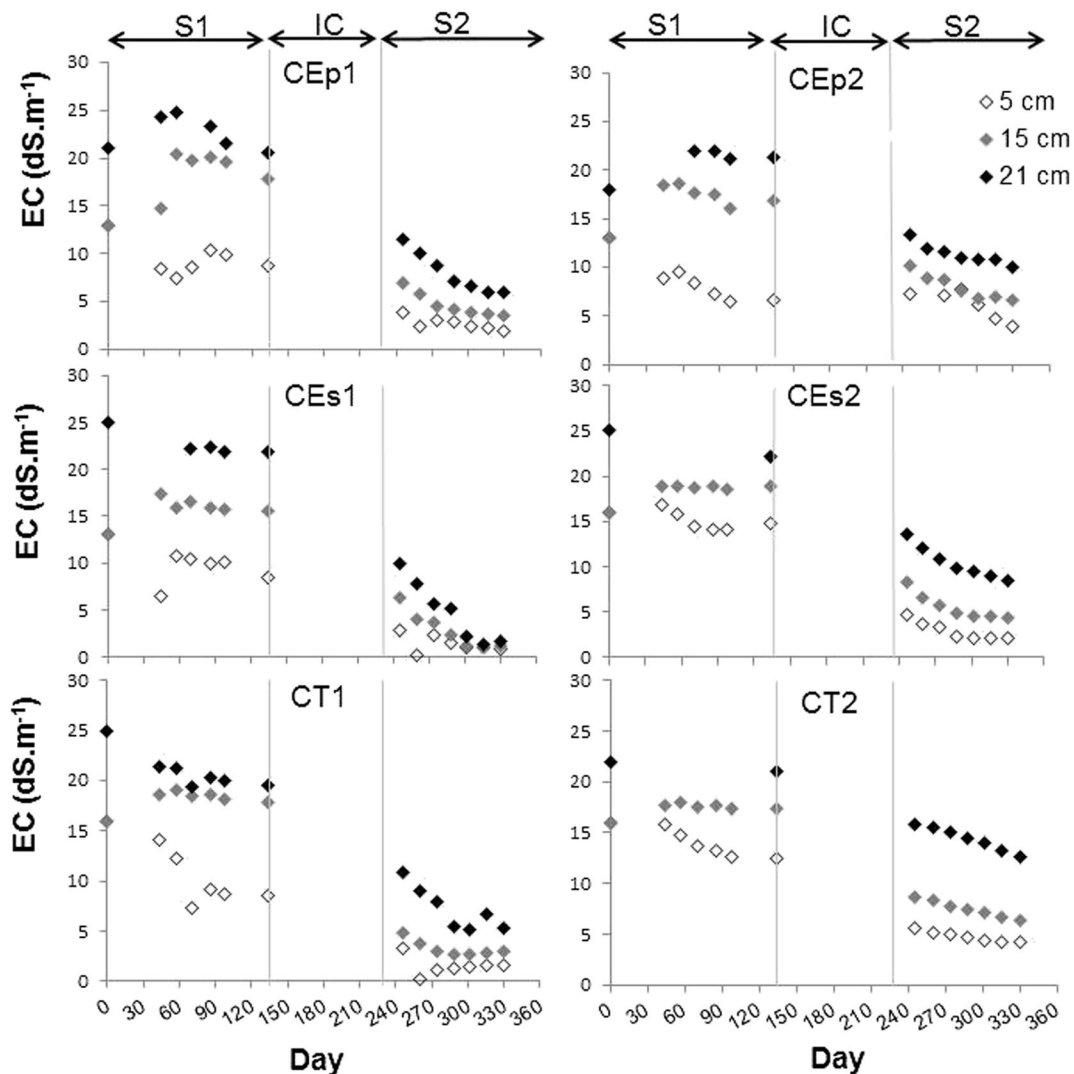


Fig. 3 Dynamics of soil solution electrical conductivity (EC) measured at depths of 5, 15 and 21 cm for each of the two instrumented soil columns of the three treatments. Treatments are

columns cultivated with permanent *Echinochloa stagnina* (CEp1 and CEp2), columns cultivated with seasonal *E. stagnina* (CEs1 and CEs2) and bare soil columns (CT1 and CT2)

correlated with the final SS ($r = -0.92$). In contrast, there was no strong or significant correlation between salt accumulated in plant biomass and soil SS.

Discussion

Changes in soil structure by *E. stagnina*

Irrigated *E. stagnina* improves the structure of saline Vertisols. After 11 months of growth, corresponding to two cropping seasons, soil BD decreased by 10–20% in soil cultivated with *E. stagnina* but barely changed in

bare soil. Moreover, soil macroporosity at ES2 was higher in cultivated soil (6–9%) than in bare soil (3–4%). Oicha et al. (2010) reported similar percentages (5–7%, i.e. $0.05\text{--}0.07\text{ m}^3\cdot\text{m}^{-3}$) of soil macroporosity in a Vertisol cultivated with *Eragrostis tef* in Ethiopia. The percentage of tubular and packing macropores, which characterizes the process of soil structuring by biological activity, was also higher in cultivated soil. However, sieving the small soil aggregates when preparing the columns and successive irrigation during the cropping seasons may have caused the soil to settle, decreasing the percentage of packing pores, particularly in bare soil. This improvement of soil structure may be explained by

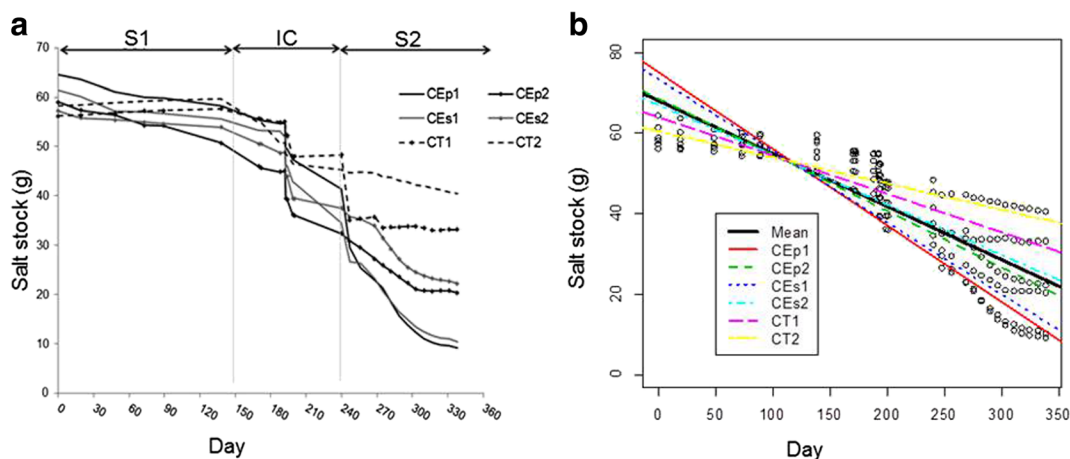


Fig. 4 (a) Dynamics of soil salt stock and (b) linear mixed models of change in soil salt stock for each treatment. Treatments are columns cultivated with permanent *Echinochloa stagnina* (CEp1 and CEp2),

columns cultivated with seasonal *E. stagnina* (CEs1 and CEs2) and bare soil columns (CT1 and CT2). S1 is the first cropping season; S2 is the second cropping period

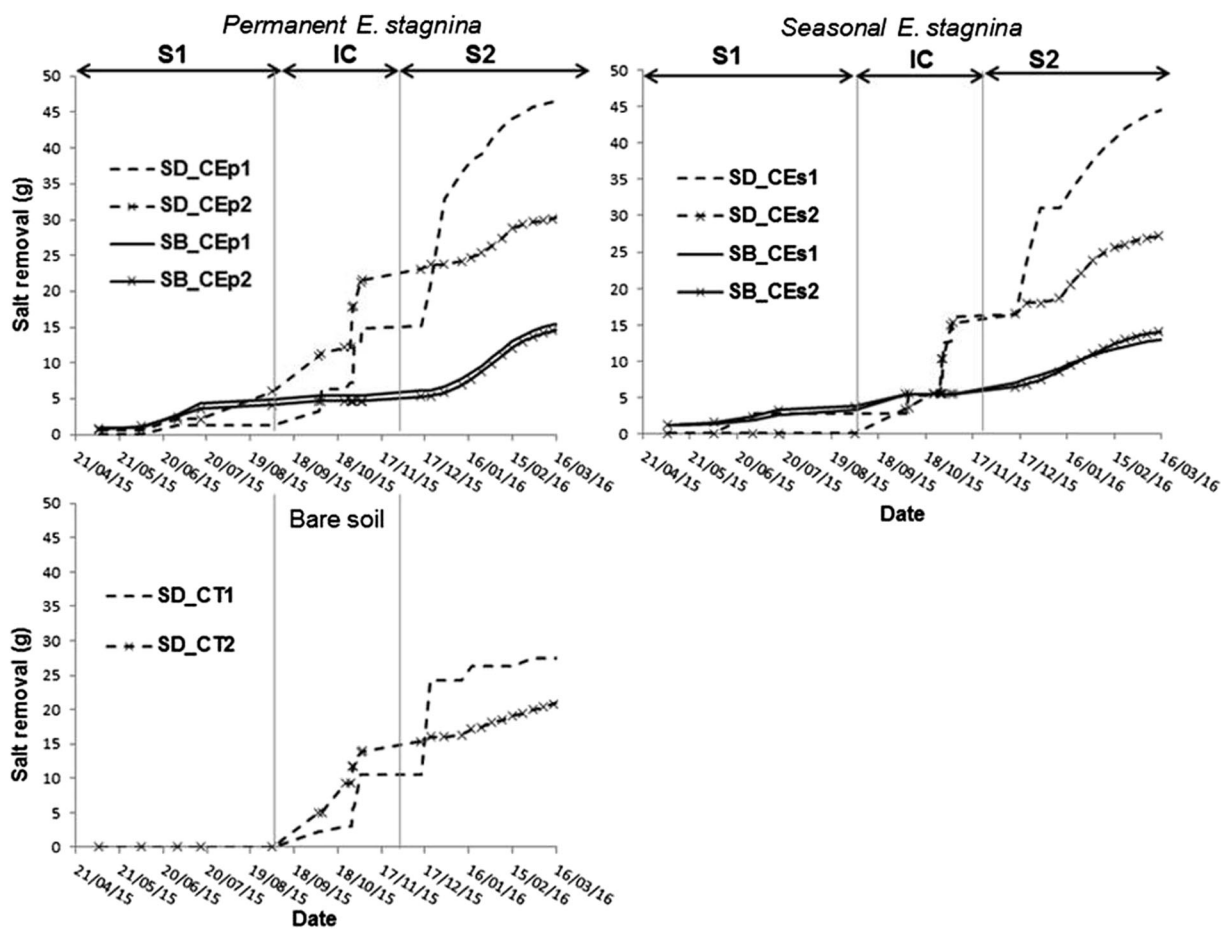


Fig. 5 Dynamics of salt removal by drainage water (SD) and aboveground plant biomass (SB) for each of the two instrumented soil columns of the three treatments. Treatments are columns cultivated with permanent *Echinochloa stagnina* (CEp1 and

CEp2), columns cultivated with seasonal *E. stagnina* (CEs1 and CEs2) and bare soil columns (CT1 and CT2). S1 is the first cropping season; S2 is the second cropping period

Table 2 Pearson correlation matrix between *Echinochloa stagnina* aboveground and root biomass, soil structure indicators (macroporosity and bulk density), soil salt stocks and the amountof salt in *E. stagnina* aboveground plant and root biomass. Bold font indicates significant correlations ($p < 0.05$)

Variable	Φ	BD	Irrig	DW	Ab	Rb	SS	SD	SB
Φ	1.00								
BD	-0.82	1.00							
Irrig	0.70	-0.50	1.00						
DW	-0.02	0.16	0.43	1.00					
Ab	0.73	-0.57	0.97	0.24	1.00				
Rb	0.63	-0.53	0.86	0.28	0.88	1.00			
SS	-0.26	0.10	-0.70	-0.90	-0.58	-0.58	1.00		
SD	0.32	-0.14	0.64	0.89	0.49	0.45	-0.92	1.00	
SB	0.71	-0.58	0.95	0.18	0.99	0.90	-0.51	0.42	1.00

Φ is soil macroporosity measured at the end of the experiment (%). BD is soil bulk density measured at the end of each cropping season. Irrig is the amount of irrigation water applied during each cropping season (g). DW is the amount of water drained during each cropping season (g). Ab is *E. stagnina* aboveground plant biomass at the end each cropping season (g). Rb is *E. stagnina* root biomass at the end of each cropping season. SS is soil salt stock at the end of each cropping season (g). SD is the amount of salt in drained by water during each cropping season (g). SB is the amount of salt in *E. stagnina* aboveground plant biomass at the end of each cropping season

the root system of *E. stagnina*, mainly its penetration, which favors soil macroporosity and soil aggregation. This interpretation is supported by the significant correlations between soil structure (macroporosity) and agronomic characteristics of *E. stagnina*, particularly its root development (Table 2). Several studies (Cabidoche et al. 2000; Akhter et al. 2004; Blanchart et al. 2004; Tan and Kang 2009) showed that plant rooting may improve the structure of saline clay soils; e.g., growing *Leptochloa fusca* on a saline-sodic sandy-clay soil for 5 years increased porosity in the 0–100 cm soil layer by 15% (Akhter et al. 2004). Furthermore, Blanchart et al. (2004) showed that the macropores of Vertisols under *Digitaria decumbus* increased by 25% after 4 years of cultivation. Cabidoche et al. (2000) also showed that tubular voids were more abundant under grassland with *D. decumbus* than in uncultivated Vertisols from Martinique. Vezzani et al. (2018) reported that the improvement of soil structure (i.e. an increase in soil aggregation and soil macroporosity) by plants may be explained by the presence of roots and soil fauna activities.

Reduction of vertisol salinity by *E. stagnina*

Irrigated *E. stagnina* significantly reduced salinity of the Vertisols. After 11 months of growth, the initial EC of soil solution had decreased by 72–94% and 54–92% at depths of 5 and 21 cm, respectively. EC reduction was

greater in cultivated soil than in bare soil, particularly in the deepest soil layer (18–25 cm). Moreover, the soil SS, initially similar in all soil columns, decreased by 65–87% in soil cultivated with *E. stagnina* but by only 34–45% in bare soil at ES2. In agreement with several studies, these results confirm the capacity of *E. stagnina* to reduce soil salinity. The reduction of Vertisol salinity by *E. stagnina* in our column study, in which drainage water removed salt, was greater than that in a field study in the Niger River valley (Ado et al. 2016). Moreover, *E. stagnina*'s capacity to reduce soil salinity in our study was similar to those of other salt-tolerant plants tested for 2 months in controlled conditions: soil EC reduced by 70% and 61% by *Beta vulgaris* and *Hordeum vulgare*, respectively, cultivated in columns with a silty soil for 2 months (Ammari et al. 2008) and by 75% by *Lotus corniculatus* cultivated in pots of vertic soil for 2 months (Aydemir and Sünger 2011).

Relative importance of salt leaching and salt phyto-accumulation

Salt leaching and salt accumulation in plant biomass were the main processes by which *E. stagnina* decreased soil salinity, as reported by several studies (Barbiero et al. 2001; Ado et al. 2016). The amount of salt leached in drainage water represented 48–75% of the initial SS in soil cultivated with *E. stagnina* and 36–46% of that in

bare soil. The mechanical effect of *E. stagnina* roots in improving soil structure, particularly increasing soil macroporosity and water drainage, may explain the removal of more salt in drainage water in cultivated soil than in bare soil. This process was reported by Logsdon (2013), who showed that plant roots can increase the number of biopore channels, which become preferential flow pathways for water infiltration and solute leaching. Moreover, Li et al. (2016) showed that hydraulic conductivity increased by approximately two to three orders of magnitude when both roots and cracks developed in landfill clay liners. These results show that plant roots are significant preferential flow pathways and should be considered in engineering design.

Salt accumulation in aboveground plant biomass was estimated at 1456–1786 kg.ha⁻¹ (i.e. 22–27% of the initial SS). Accumulation in plant biomass thus contributed 22–35% of soil desalinization vs 65–78% due to leaching. Ado et al. (2016) found lower percentages in a field experiment in Niger: 664–720 kg.ha⁻¹ of salt accumulated in plant biomass of *E. stagnina* after 8 months of growth (i.e. 11–12% of the initial SS in the 0–10 cm soil layer). This difference may be explained by the initial sieving of small aggregates in columns, which would increase salt dissolution and favor salt accumulation in plant biomass. Other salt-tolerant plants - *Atriplex aucheri*, *Suaeda salsa* and *Salicornia europaea* - were shown able to accumulate 7619, 5258 and 4828 kg.ha⁻¹ of salt, respectively, after one year of growth (Zhao et al. 2013). Likewise, *Beta vulgaris* and *Hordeum vulgare* exported 306 and 212 kg.ha⁻¹ of salt, respectively, in their biomass after 65 days of growth (Ammari et al. 2008).

In contrast, several authors (Qadir et al. 2000, 2003; Yan et al. 2016) argued that salt accumulation in plant biomass contributed only slightly to soil desalinization. In a silty-clay soil without drainage, Qadir et al. (2003) observed that the amount of sodium accumulated in *Medicago sativa* biomass represented only 1.4% of sodium removal in the topsoil vs 98.6% due to leaching. These authors concluded that leaching was the main process of soil desalinization. In contrast, our study showed that salt accumulation in plant biomass contributes significantly to soil desalinization, as reported by other studies (Rabhi et al. 2010; Zhao et al. 2013). These studies found that salt accumulation in plant biomass decreased soil SS considerably. Several authors (Rabhi et al. 2010; Jesus et al. 2015) consider that the relative importance of processes contributing to

phytodesalinization (e.g. leaching and phyto-accumulation) depends on plant species, soil and climate. For example, Rabhi et al. (2010) showed that *Tamarindus indica* and *Salvia fruticosa* accumulate more sodium in winter than in summer in a semi-arid climate in Tunisia because plant photosynthesis was more active in winter than in summer. Some plants can accumulate large amounts of salt but produce relatively little biomass, whereas other plants accumulate little salt but produce large amounts of biomass (Jesus et al. 2015).

Agronomic potential of *E. stagnina*

E. stagnina can produce a large amount of forage in aboveground biomass and a strong root system. During each cropping season in the laboratory experiment, *E. stagnina* produced the equivalent of 3–8 t.ha⁻¹ of dry weight biomass (i.e. 10–12 t.ha⁻¹ of total dry weight biomass for two seasons), less than that under field conditions (24–27 t.ha⁻¹ of dry weight biomass after 8 months of growth) (Ado et al. 2016). These yields are similar to those of fodder grasses in the Niger River valley (10–30 t.ha⁻¹ of dry weight biomass per year) (Dieter and Hassane 2001). They are also similar to observed yields of *Hordeum vulgare* and *Beta vulgaris* (4 and 3 t.ha⁻¹ of dry weight biomass, respectively) after 2 months of growth on silty soil columns (Ammari et al. 2008).

Moreover, *E. stagnina* developed a dense root system on soil columns (Online Resource 4). Dry root biomass of *E. stagnina*, estimated at 1–3 t.ha⁻¹ per cropping season, represented 20–25% of total dry plant biomass and filled 2–9% of the total soil volume (Online Resource 2). *E. stagnina* crop appears as an effective ecological engineering approach to improve physical properties and reduce the salinity of Vertisols and to produce forage.

Conclusion

This study tested the capacity of the semi-aquatic grass *E. stagnina* to improve the structure and decrease the salinity of saline Vertisols. The experimental study, conducted on soil columns under laboratory conditions for 11 months for two cropping seasons, showed that soil cultivated with *E. stagnina* had higher macroporosity (6–9%) than bare soil (3–4%). SS, which was initially similar in all columns, decreased by 65–87% in soil

cultivated with *E. stagnina* and by 34–45% in ponded bare soil. Salt leaching and accumulation in plant biomass were shown as the main processes of soil desalinization by *E. stagnina*. Future studies must investigate the relationship between soil hydrodynamic parameters and agronomic characteristics of *E. stagnina*, e.g. by modelling approaches, to assess the relative importance of different processes in phytodesalination of Vertisols. In addition, *E. stagnina* produced 10–12 t.ha⁻¹ of dry weight biomass in 11 months, which makes it of economic interest for farmers. Thus, an irrigated crop of *E. stagnina* appears an effective method to restore saline Vertisols by improving their structure and contributing to their desalinization.

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