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Comparison of growth of annual crops used for salinity bioremediation in the semi-arid irrigation area

Kidia K. Gelaye[1,2]*, *Franz Zehetner*[3], *Willibald Loiskandl*[1], *Andreas Klik*[1]

[1]*Department of Water-Atmosphere-Environment, Institute of Hydraulics and Rural Water Management, University of Natural Resources and Life Sciences Vienna, Vienna, Austria*
[2]*Samara University, Samara, Ethiopia*
[3]*Department of Forest and Soil Sciences, Institute of Soil Research, University of Natural Resources and Life Sciences Vienna, Vienna, Austria*

**Corresponding author: kkidia3@gmail.com*

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Abstract: The decline of soil organic carbon (SOC) has aggravated salinity-related problems in semi-arid irrigation areas of the Awash river basin, Ethiopia. This study aimed at evaluating the performance of potential remediation crops on saline soil and their effectiveness for remediating soil salinity and improving pH, SOC, bulk density (BD) and hydraulic conductivity (HyCo). Rhodes grass (RHG), alfalfa (ALF), sudangrass (SUG) and blue panicgrass (Retz) (BPG) were grown in saline (3–13.9 dS/m) field plots. The crop biomass was incorporated into the soil immediately before flowering. The results show that at high soil salinity levels, BPG and SUG grew well, with the harvesting frequency of BPG being much higher than for SUG. Conversely, the growth of ALF and RHG was strongly inhibited by high soil salinity. Significant ($P < 0.05$) reduction of soil salinity levels (–3.2 dS/m) and related ionic concentrations, an increase of SOC (0.8% to 1.6%) and improvement of BD and HyCo were observed in BPG plots. The fast-growing nature of BPG in the hot climate of the experimental area resulted in harvests every three weeks and promoted the incorporation of high amounts of biomass to the soil and efficient soil salinity remediation. At moderately saline conditions, ALF also showed a great potential for salinity reclamation (–1.8 dS/m) and SOC accumulation. The cultivation of fast-growing annual crops proved an efficient and low-cost strategy for soil salinity mitigation and the reclamation of salinity-associated soil degradation in irrigation agriculture in Ethiopia.

Keywords: salt tolerance; arid conditions; drought; land degradation; forage

Soil salinity is a major constraint in arid and semi-arid agricultural production. Soil salinity problems are more severe in situations where inadequate irrigation drainage leads to salt accumulation in the soil (Hanin et al. 2016). In the eastern and southern arid and semi-arid parts of Ethiopia, nearly 12 million hectares of land are affected by salt (Taddese 2001). Compared to other Ethiopian rivers, Awash is the river most used for irrigation purposes. However, due to rapid salt accumulation, Awash river irrigation farms have been losing between 200 and 300 hectares of cultivated land annually (Behnke and Kerven 2011). Lack of functional drainage systems, poor irrigation management, shallow groundwater fluctuation (Taddese 2001), improper irrigation canal installations and continuous loss of soil organic carbon (SOC) in mono-cropping fields are the main causes for salinity and land degradation in the Awash basin.

The large-scale Awash basin irrigation schemes are cultivated with commercial cash crops, such as cotton and sugarcane. The commercial crops have been cultivated for years with mono-cropping methods. Such practice caused a decline in soil organic carbon in the irrigated fields, which, in turn, led to structural degradation and increased risk of soil salinity and sodicity. Beyond the irrigation farmlands, in the Awash basin overgrazing and unexpected droughts have had a negative impact on soil (Taddese 2001). Nowadays, low SOC contents, high sodicity and salinity have degraded the grazing land ecosystems

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and favoured opportunistic invasive species in arid areas of the basin. This poses ecological, cultural and socio-economic challenges for the pastoralism of the Afar people.

The use of bioremediation for irrigated and grazing land may constitute a vital strategy for sustainable agriculture. Fast-growing and salt-resistant crops may be planted on fallow irrigated land or interplanted for animal feed or salinity bioremediation. A study by Wong et al. (2010) showed that the addition of organic material to saline soils resulted in increased soil microbial biomass and enhanced the decomposition and conversion of plant biomass into SOC. Especially the entire plant biomass regularly incorporated into the soil at an early growth stage heightens the accumulation of SOC and promotes the restoration to crop favourable soil bulk density and hydraulic conductivity. Accumulation of SOC near the soil surface was shown to improve soil hydraulic properties (Benjamin et al. 2007, Ammari et al. 2013), thus promoting drainage and favouring the leaching of accumulated salts.

An essential prerequisite for devising salinity mitigation strategies using bioremediation is the identification of plants that are salt-tolerant and fast-growing under given environmental conditions. Therefore, this field study was conducted to compare the performance and mitigation efficiency of four annual crops with potential for forage production on saline fields in Ethiopia. The aim was to identify the crop(s) with the highest biomass production rate under saline conditions and evaluate their potential for soil salinity reduction and improvements of basic soil properties, such as pH, SOC, bulk density and hydraulic conductivity.

MATERIAL AND METHODS

Study area. The Kesem river is one catchment area in the middle part of the Awash river basin in Ethiopia. This research was conducted at the Kesem irrigation scheme, which is located at 9°8'54.8''N and 40°1'6.57''E and at an elevation of 770 m a.s.l. According to the World Reference Base, the excremental soil was grouped to Fluvisols (IUSS Working Group, WRB 2015). The soil texture of the experimental field is sandy loam and mean soil bulk density is 1.3 g/cm^3. The groundwater table is 2.8 m below the soil surface. Annual temperature varies from 18°C to 41°C; mean annual rainfall is approximately 590 mm. The salinity of the irrigation water was 0.32 dS/m, the pH 7.6. The mean soil salinity of the experimental plots varied between 3.0–16 dS/m and soil pH was 7.7.

Experimental setup. The experiment was arranged in a randomized complete block design with three replications. Fast-growing annual crops were used for this experiment: (1) Rhodes grass (RHG) (*Chloris gayana*); (2) alfalfa (ALF) (*Medicago sativa*); (3) sudangrass (SUG) (*Sorghum* × *drummondii*); (4) blue panicgrass (BPG) (*Panicum antidotale*, Retz) and (5) an open bare field/control. Hence, a total of 15 experimental plots were established. The size of each plot was 3 m in width and by 33 m in length. The experimental crops were densely planted in early February 2016 and grown until the end of July 2017. An equal amount of irrigation water was supplied to each planted plot using a surface irrigation method and a surface drainage ditch was established across all experimental plots. No soil fertilization was used. Weeds were removed manually every week, however, during the experimental season, neither plant diseases nor pests were observed. During the experimental seasons, fresh plants biomass was cut before flowering, chopped manually (3–5 cm) and immediately after harvesting it was incorporated into the soil (at 0–20 cm depth). Plant dried biomass was determined by weighing the total air dried above ground biomass yield.

Soil properties measurement. Soil samples before seed sowing (initial) and after two months of the final biomass incorporation (final) were taken from 0–30 cm and 30–60 cm soil depth. Each experimental plot of disturbed composite soil sample was prepared of four soil probes. Soil salinity ($EC_{1:5}$) and $pH_{1:5}$ were measured at a 5 g/25 mL soil/water ratio (Khorsandi and Yazdi 2011). The soil SOC was oxidized with 1 mol/L potassium dichromate ($K_2Cr_2O_7$) solution and determined according to Walkley and Black (1934). For soluble cations and anions, soil samples were extracted at 1:2 soil/water ratio. In the extract, Mg^{2+} and Ca^{2+} were determined by titration with disodium dihydrogen-ethylenediaminetetraacetate (EDTA) (Tucker and Kurtz 1960), and Na^+ and K^+ were measured by the flame photometric method (Woldring 1953). The anions CO_3^{2-} and HCO_3^- were determined by titration with H_2SO_4. Chloride was determined by titration with $AgNO_{3;}$ SO_4^{2-} was determined gravimetrically after precipitation with $BaCl_2$. For each plot, (*in-situ*) saturated hydraulic conductivity was measured using a Guelph permeameter (Soilmoisture Equipment Corporation 2012). For soil bulk density, undisturbed soil core samples

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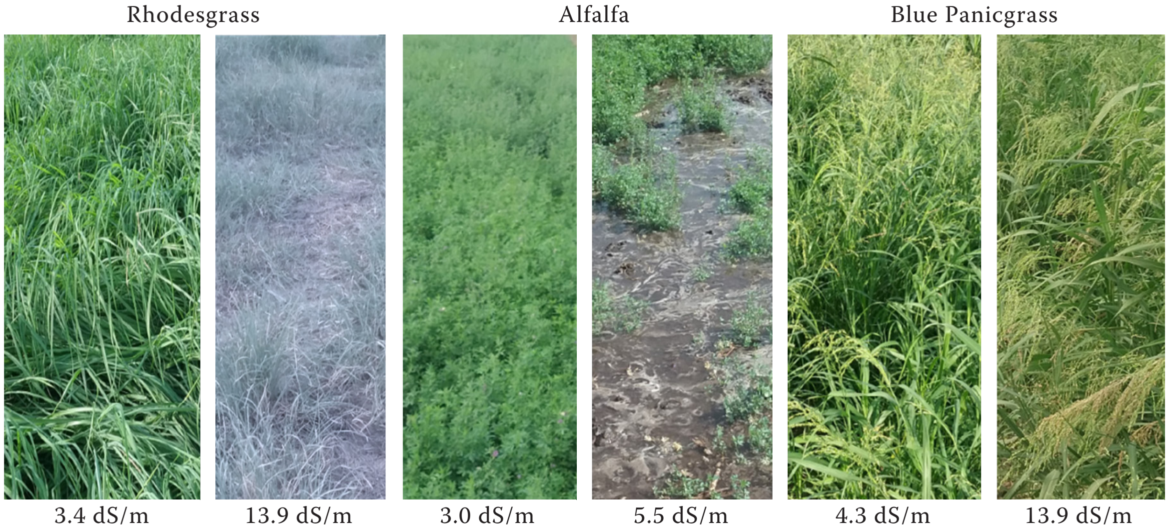

Figure 1. Crop performance evaluation at different soil salinity levels

were taken with cylinders and oven-dried to constant mass (McIntyre and Loveday 1974).

Soil property improvement was expected through mitigation effects of the tested crops, supported by salinity removal with the irrigation water; approximately 15% of the irrigation water was applied as surplus leaching water to the experimental plots (0.13 estimated required leaching water). The leachate water was drained through the established surface drainage or down-migrated to the groundwater.

Statistical analysis. One-way analysis of variance (ANOVA) was performed and comparisons of means were conducted using the Tukey's post-hoc test (P < 0.05) with R (R Core Team 2018).

RESULTS

Crop performance on saline soil. The growth performance of the tested mitigation crops was visually examined at regular intervals. Among the four mitigation crops planted, BPG and SUG performed well regardless of the soil salinity level of the experimental plots. However, ALF and RHG showed poor tolerance at higher soil salinity levels. BPG was evaluated at medium to very high salt contents (4.3–13.9 dS/m), but the growth performance was slightly affected by higher salt levels (Figure 1). Conversely, at more saline plots, RHG and ALF showed stunted growth and large parts of the plots were uncovered by vegetation (Figure 1). Nevertheless, RHG at 3.4 dS/m and ALF at 3.0 dS/m showed dense growth, similar to BPG. After 1.5 months of growth establishment, BPG started growing fast with high numbers of tillers and its height reached 1.5 m; its fresh biomass could be incorporated into the soil every three weeks. However, for RHG, ALF and SUG, the required growth periods until biomass incorporation were extended beyond a month.

Effect of crops biomass on soil SOC, bulk density and hydraulic conductivity. The significant (P < 0.05) amount of biomass was shown in the BPG plant compared to ALF and RHG plants (Figure 2). As a result, BPG caused a strong increase in SOC down to 60 cm depth (Table 1). Per harvesting 7.5 t/ha dried biomass was continuously incorporated into the BPG plots, and cumulatively SOC increased by 100%. At ALF and RHG plants less biomass was incorporated

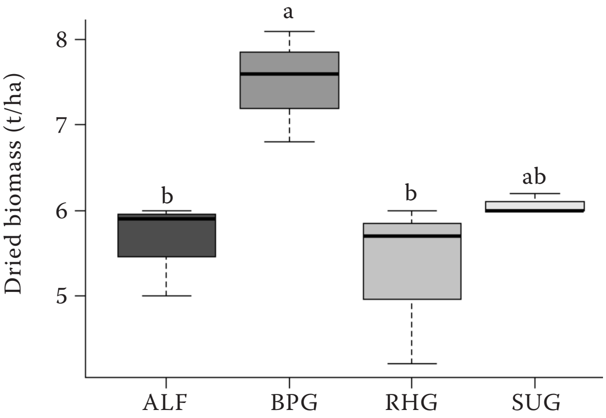

Figure 2. Initial and final soil salinity and changes from initial to final values. Error bars represent standard deviation. Different letters indicate a significant difference between treatments at P < 0.05 using the *LSD* (least significant difference) *F*-test. ALH – alfalfa; BPG – blue panicgrass; RHG – rhodes grass; SUG – sudangrass

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and lower SOC accumulation was observed recorded compared to BPG because the germination, growth and biomass of these two crops were compromised in highly saline plots. On the other hand, the produced biomass of SUG plant was slightly higher than at ALF and RHG. Meanwhile, in the bare soil of the control, SOC declined by 0.1% (Table 1).

The planted mitigation crops led to decreases in soil bulk density, especially in BPG and SUG plots (Table 1). These changes were most pronounced in the upper layer (0–30 cm), but for BPG and SUG, they were also discernible at 30–60 cm soil depth. Morever, saturated hydraulic conductivity was enhanced by the tested mitigation crops, most notably in the BPG plots (Table 1).

Changes in soil salinity and pH. Our results show that salinity was substantially reduced at both depths in all planted plots (Figure 3), while soil pH showed a slight increase with salt reduction except in control plots (Figure 4). The observed salinity reduction ranged between 1.5 and 3.4 dS/m (Figure 3) and was most pronounced for BPG, which was able to significantly reduce soil salinity also in 30–60 cm soil depth. Among the investigated crops, the minimum salt reduction was observed for RHG. In the top part of the root zone (0–30 cm), salinity reduction was higher than in the lower part (30–60 cm) (Figure 3). Before the experiment, salt was predominantly accumulated at the top layer of the soil, but after the experiment, the differences between upper and lower depth decreased.

For soil pH, the final pH result showed highly significant ($P < 0.01$) variation between the tested crops and control field at 0–30 cm and 30–60 cm depths (Figure 4). However, insignificant pH variations were observed among mitigate plants. Differently from the control plots, the pH increased in all planted plots as salt content was reduced during the experiment.

Changes in soluble saline ions. Calcium cations and chloride anions were the dominant soluble ions in the studied plots, followed by sodium and sulfate (Table 2). Hence, the dominant salt in the experimental field was $CaCl_2$. Our results show that BPG was most effective among the tested crops in reducing the levels of the investigated cations from both soil depths. For instance, at 0–30 cm depth, the average concentrations of soluble Ca^{2+} and Na^+ were reduced by 9.6 and 4.0 $mmol_c/L$, respectively. On the other hand, the changes of most anions were non-significant ($P < 0.05$) between treatments, while Cl^- and SO_4^{2-} ions were reduced by 4.4 and 1.9 $mmol_c/L$ at BPG plots (Table 2). Depletion of these salinity-causing ions has a direct impact on soil salinity reduction. Besides BPG, ALF and RHG also showed a notable reduction of saline-causing ions at 0–30 cm soil depth.

DISCUSSION

The growth of the mitigation crops and the continuous incorporation of their biomass to the soil changed the soil properties in many aspects. It was found that besides mitigating soil salinity and the concentrations of soluble saline ions, the crops also affected pH, soil SOC content, bulk density and hydraulic conductivity. Salinity reduction and modi-

Table 1. Initial (before crop planting) and final (after the experiment) soil physical properties (mean ± standard deviation; $n = 4$)

Depth (cm)	Crop	Organic carbon (%)		Bulk density (g/cm^3)		Saturated hydraulic conductivity (Kfs, mm/h)	
		initial	final	initial	final	initial (0–40 cm)	final (0–40 cm*)
0–30	RHG	0.9 ± 0.1	1.3 ± 0.5^{ab}	1.3 ± 0.1	1.2 ± 0.1^{ab}	4.8 ± 1.4	5.8 ± 1.3^{a}
	SUG	0.9 ± 0.1	0.9 ± 0.2^{b}	1.4 ± 0.0	1.1 ± 0.1^{ab}	4.5 ± 2.3	5.9 ± 1.0^{a}
	BPG	0.8 ± 0.1	1.6 ± 0.1^{a}	1.4 ± 0.1	1.0 ± 0.0^{a}	7.0 ± 2.2	9.2 ± 0.4^{b}
	ALF	0.7 ± 0.1	1.2 ± 0.4^{ab}	1.4 ± 0.0	1.2 ± 0.1^{ab}	8.0 ± 1.6	9.0 ± 1.4^{b}
	CRL	0.8 ± 0.2	0.7 ± 0.2^{b}	1.3 ± 0.1	1.3 ± 0.1^{b}	6.0 ± 1.5	6.3 ± 1.6^{a}
30–60	RHG	0.6 ± 0.2	0.7 ± 0.2^{ab}	1.2 ± 0.2	1.0 ± 0.0^{a}		
	SUG	0.5 ± 0.1	0.5 ± 0.1^{b}	1.3 ± 0.2	1.0 ± 0.0^{a}		
	BPG	0.5 ± 0.2	1.1 ± 0.3^{a}	1.3 ± 0.1	1.0 ± 0.0^{a}		
	ALF	0.6 ± 0.2	0.8 ± 0.4^{ab}	1.3 ± 0.1	1.0 ± 0.0^{a}		
	CRL	0.6 ± 0.1	0.6 ± 0.1^{b}	1.2 ± 0.1	1.0 ± 0.0^{a}		

*measured soil depth using permeameter. Different letters indicate a significant difference between treatment means at $P < 0.05$. RHG – rhodes grass; SUG – sudangrass; BPG – blue panicgrass; ALH – alfalfa; CRL – control

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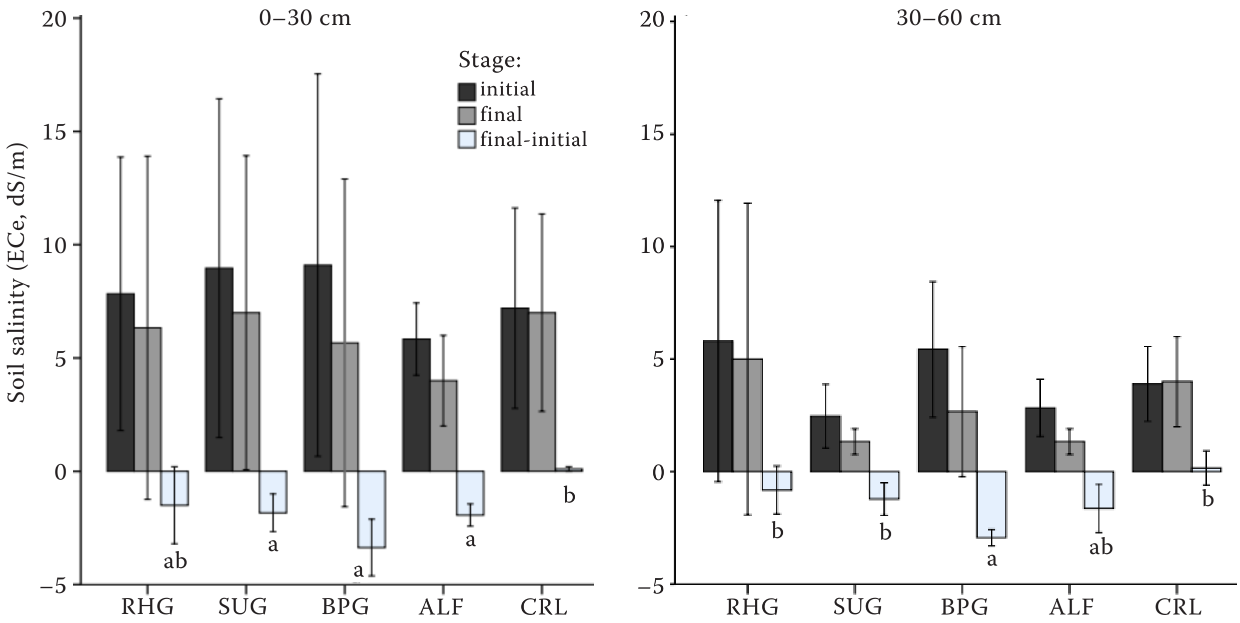

Figure 3. Initial and final soil salinity and changes from initial to final values. Error bars represent standard deviation. Different letters indicate a significant difference between treatments at $P < 0.05$ using the *LSD* (least significant difference) *F*-test. RHG – rhodes grass; SUG – sudangrass; BPG – blue panicgrass; ALH – alfalfa; CRL – control

fication in soil properties were most pronounced with BPG biomass incorporated to the soil, due to its high amount. Next to BPG, the SUD produced high amount of biomass to be incorporated, however, in these plots, the SOC, bulk density and hydraulic conductivity were not improved like at other crops plots. Harvesting frequency played a considerable role for high incorporation of biomass and improvements of soil properties. During this experiment, BPG was harvested every 21 days, whereas SUG, ALF and RHG were harvested in 35-day interval. The ability of BPG to grow under high salinity guaranteed good growth performance at the salinity levels encountered in our experimental field (4–13.9 dS/m) and resulted in con-

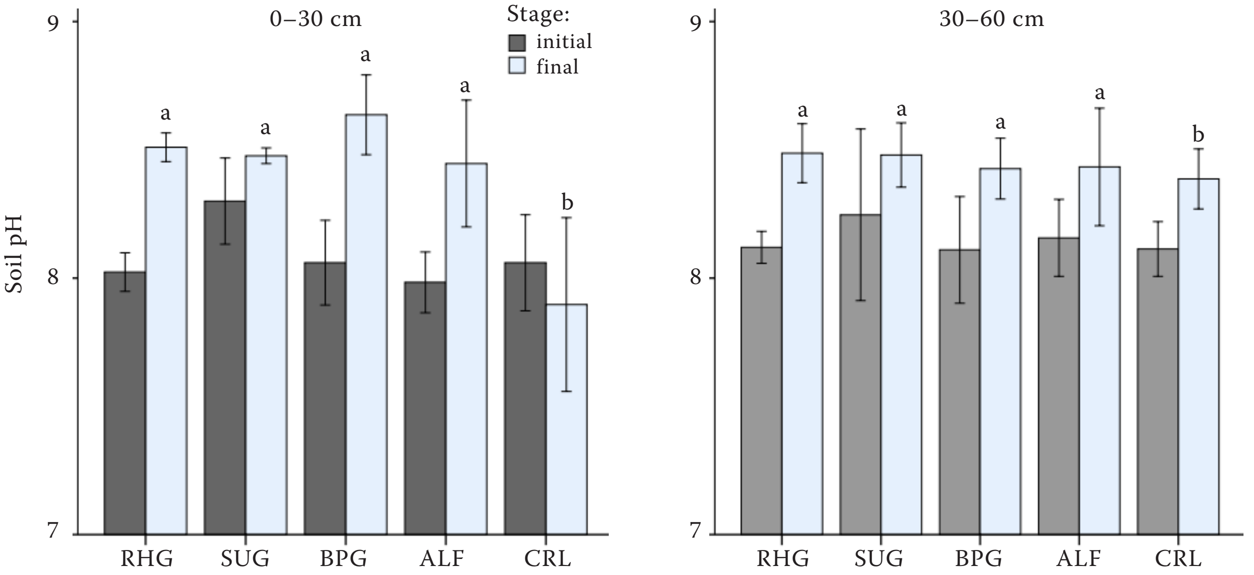

Figure 4. Initial and final soil pH. Error bars represent standard deviation. Different letters indicate significant difference in pH between treatments at $P < 0.01$ using the *LSD* (least significant difference) *F*-test. RHG – rhodes grass; SUG – sudangrass; BPG – blue panicgrass; ALH – alfalfa; CRL – control

Table 2. Cations and anions (mmol$_c$/L) in soil water extracts; initial and final levels (mean ± standard deviation; n = 4)

Depth/ Crop	Na^+		K^+		Mg^{2+}		Ca^{2+}		HCO_3^-		Cl^-		SO_4^{2-}	
	initial	final	initial	final	initial	final	initial	final	initial	final	initial	final	initial	final
0–30 cm														
RHG	8.2 ± 6.7	6.8 ± 7.8^{a}	0.9 ± 0.3	0.8 ± 0.9^{a}	3.6 ± 1.7	1.0 ± 0.4^{ab}	21.1 ± 12.8	18.0 ± 14.4^{a}	0.9 ± 0.2	0.5 ± 0.3^{a}	17.7 ± 19.0	14.2 ± 20.5^{a}	6.3 ± 2.6	4.6 ± 3.6^{a}
SUG	5.1 ± 4.2	3.6 ± 3.6^{a}	0.5 ± 0.1	0.3 ± 0.1^{a}	2.7 ± 2.0	0.7 ± 0.8^{a}	13.3 ± 4.5	10.4 ± 4.6^{a}	1.4 ± 0.4	1.1 ± 0.4^{b}	8.7 ± 4.6	5.9 ± 3.4^{a}	6.3 ± 2.6	4.1 ± 1.8^{a}
BPG	9.8 ± 8.0	5.8 ± 6.3^{a}	1.0 ± 0.9	0.6 ± 0.7^{a}	6.5 ± 3.7	3.5 ± 2.7^{bc}	26.1 ± 24.9	16.5 ± 18.6^{a}	1.6 ± 0.3	0.5 ± 0.1^{a}	21.5 ± 19.3	17.1 ± 20.0^{a}	5.7 ± 2.6	3.9 ± 2.4^{a}
ALF	4.0 ± 0.9	3.1 ± 0.9^{a}	0.6 ± 0.3	0.3 ± 0.2^{a}	3.6 ± 1.8	1.6 ± 1.2^{ab}	15.3 ± 4.6	12.4 ± 4.2^{a}	1.4 ± 0.2	0.9 ± 0.3^{ab}	8.5 ± 3.2	4.3 ± 3.8^{a}	5.1 ± 3.0	3.9 ± 1.3^{a}
CRL	4.3 ± 0.6	3.6 ± 0.5^{a}	0.6 ± 0.2	0.6 ± 0.7^{a}	4.3 ± 0.8	4.0 ± 0.6^{c}	19.0 ± 11.5	19.4 ± 10.7^{a}	1.3 ± 0.1	0.6 ± 0.2^{ab}	16.5 ± 11.6	15.9 ± 11.3^{a}	4.0 ± 1.0	4.0 ± 1.0^{a}
30–60 cm														
RHG	5.2 ± 3.2	4.2 ± 3.3^{a}	0.6 ± 0.3	0.6 ± 0.8^{a}	2.0 ± 1.6	3.1 ± 2.2^{a}	11.6 ± 2.6	8.6 ± 3.5^{a}	0.7 ± 0.4	0.3 ± 0.6^{a}	9.8 ± 11.8	8.4 ± 11.8^{a}	3.4 ± 1.7	3.4 ± 1.7^{ab}
SUG	3.5 ± 1.0	2.9 ± 0.6^{a}	0.2 ± 0.1	0.1 ± 0.0^{a}	1.3 ± 0.7	4.3 ± 0.6^{a}	7.0 ± 0.6	4.7 ± 0.9^{a}	0.9 ± 0.5	0.7 ± 0.6^{ab}	5.3 ± 4.3	3.8 ± 3.5^{a}	2.8 ± 1.0	1.1 ± 1.0^{a}
BPG	6.3 ± 4.3	4.7 ± 3.3^{a}	0.5 ± 0.4	0.2 ± 0.0^{a}	2.5 ± 2.3	2.5 ± 1.1^{a}	13.5 ± 13.3	9.3 ± 10.5^{a}	1.3 ± 0.3	1.0 ± 0.0^{ab}	13.3 ± 10.2	11.2 ± 9.8^{a}	4.6 ± 2.6	3.9 ± 2.8^{ab}
ALF	3.6 ± 0.5	3.2 ± 0.9^{a}	0.4 ± 0.2	0.3 ± 0.2^{a}	1.2 ± 1.0	4.4 ± 1.7^{a}	9.7 ± 2.3	5.8 ± 1.2^{a}	1.3 ± 0.5	1.0 ± 0.0^{ab}	5.3 ± 2.2	2.3 ± 1.0^{a}	4.0 ± 1.0	2.8 ± 1.0^{ab}
CRL	4.0 ± 0.2	4.0 ± 0.8^{a}	0.2 ± 0.1	0.4 ± 0.4^{a}	1.6 ± 1.9	2.7 ± 1.3^{a}	9.4 ± 7.7	9.3 ± 7.3^{a}	1.2 ± 0.2	1.3 ± 0.6^{b}	9.8 ± 8.5	11.0 ± 8.7^{a}	4.6 ± 2.0	4.5 ± 1.8^{b}

Different letters indicate a significant difference between treatment means at $P < 0.05$. RHG – rhodes grass; SUG – sudangrass; BPG – blue panicgrass; ALH – alfalfa; CRL – control

siderable improvements of soil physical and chemical properties. Similarly, Hussain et al. (2015) reported that moderate sodium chloride salinity (12.5 dS/m, NaCl) had a little effect on the BPG growth. Remarkably, very similar growth performance of BPG was observed at all experimental plots despite different salinity levels; however, (relatively) higher salinity reduction was observed in plots with lower salt content. For instance, the salt level of 13.9 dS/m was reduced to 10 dS/m, while 4.0 dS/m was reduced to 1 dS/m.

The fast-growing nature of BPG in the hot climate of the experimental site shortened the harvesting interval of BPG to only three weeks. At flowering initiation, BPG was already 1.5 m tall. This observation was corroborated by Ahmad et al. (2010) who reported that BPG could reach a height of 2 m or more. By comparison, the other tested crops required more than one month until harvest. The superior biomass production of BPG in our experiment was also reflected in superior salinity mitigation and stronger improvement of soil physical and chemical properties when compared to the other tested crops. Despite water and salinity stress under arid conditions, BPG forage production was observed to be high compared to the other forage crops such as ALF (Ismail and El-Nakhlawy 2018). Also, Hussain et al. (2015) recommended that BPG can be grown sustainably as a fodder crop in saline arid regions. Our results support this recommendation for the context of the Awash river basin, Ethiopia; this will constitute a promising strategy to restore saline abandoned irrigated fields and to supplement needed forage.

In our experiment, BPG's high biomass production resulted in a pronounced increase in SOC contents, with favourable effects on bulk density and hydraulic conductivity (Table 1). OC and soil organic matter is a direct effect of biomass incorporation. SOC accumulation plays an important role in this context as it helps stabilize soil structure and thus promotes water infiltration/percolation. Benjamin et al. (2007) reported that increasing organic matter in soil has the potential to improve soil hydraulic properties by increasing macroporosity.

This experimental results show the importance of soil SOC accumulation in promoting soil conditions that favour salinity mitigation with the reduced amount of leaching water. As the soil hydraulic conductivity increases, the migration of salts from the root zone topsoil to the groundwater is promoted (Bayabil et al. 2015). This experiment results show that the biomass accumulation and bulk density reduction promote the hydraulic conductivity of the soil that result in the down percolation of salts and some free existing cations remain on the top layers of the soil, which promotes the increase of the soil pH.

Several studies have shown the negative relationships between SOC and soil compaction (Zhang et al. 1997, Brevik et al. 2002, Mamman et al. 2007). SOC reduces soil compaction and amends other soil properties. For instance, it increases the hydraulic conductivity (Benjamin et al. 2007), reduces soil bulk density and increases the probability of salt removal from the surface to deeper soil profiles through applied leaching water.

The distribution of salts in the field is neither uniform nor constant (Ayars et al. 2011). In our experiment, saline ions were dominant near the soil surface (0–30 cm), with double the amount compared to the lower profile (Table 2). However, after the experiment, when other ions were preferentially removed, the (relatively increased) remaining Na^+ increased the pH level of the soil (Figure 4). However, the irrigation water used in this experiment had very low salinity levels, which could not have had significant effects on the sodium levels in the soil.

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