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Salt and water dynamics of irrigated vertisols cultivated with fodder crop of *Echinochloa stagnina* in Niger River valley

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Irrigating Vertisols to produce crops, such as rice, alters its hydrological regime and often degrades the soil, particularly through waterlogging and salinization. The objective of this study was to evaluate the effects of the fodder crop *Echinochloa stagnina* on the salt and water dynamics of saline vertisols, in comparison to an irrigated paddy system in the Niger River valley. The study was conducted in irrigated paddy fields in the Niger River valley, using an experimental design with four treatments: (i) submerged bare soil without crops (PT), (ii) soil cultivated with rice (PR) over two successive cropping seasons, (iii) soil cultivated with *E. stagnina* over two successive seasons (PEs) with a complete harvest in between, and (iv) soil permanently cultivated with *E. stagnina* (PEp) with staggered harvests. The results showed that water table fluctuations were positively correlated with soil salt stock, especially in deeper layers. The salt stock decreased significantly over time under irrigated *E. stagnina* crops. After 15 months, the initial salt stock decreased by 33 to 36% under *E. stagnina* crops, compared to only 4% under the rice crop and submerged bare soil in the 0 to 60 cm layer. Crop diversification in paddy systems, with the introduction of *E. stagnina* as a fodder crop, appears to be a promising agroecological approach for soil and water conservation by promoting soil desalination and ensuring the sustainability of irrigated paddy systems in Niger.

Key words: Irrigation, vertisols, soil salinity, soil and water management, *E. stagnina*.

INTRODUCTION

In Africa, particularly in Sahel countries, agriculture—the main economic sector—produces most of the basic foodstuffs and serves as the sole source of livelihood and income for more than half of the population, which continues to grow (FAO, 2001; Geneste, 2013). Given the projected population and income growth, meeting future food demand will place unprecedented pressure on the limited resources of water, fertile land, and energy (Khan et al., 2021). The sustainability of food and agricultural systems is under stress due to global

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demographic changes, including rapid population growth, increased food demand, climate change effects, and limited water supplies (Khan et al., 2021). Irrigation is a crucial factor for the sustainability of food and agricultural systems, especially in arid and semi-arid regions like Niger, where irregular rainfall limits agricultural production (Mahamane et al., 2005; Foley et al., 2011). In Niger, irrigated agriculture contributes 14% of the agricultural Gross Domestic Product and 90% of export revenue from crop production (FAO, 2005). However, irrigation alters the soil's hydrological regime and often degrades it, particularly through waterlogging and soil salinization (Favre, 1997; Houk et al., 2006). Soil salinity caused by irrigation is a major constraint to agriculture, especially in arid and semi-arid zones, due to water scarcity and high evaporation rates (Ado et al., 2022). Most reductions in crop yield are attributed to salt accumulation in the soil (Shrivastav and Kumar, 2015). It is estimated that 33% of irrigated agricultural land worldwide is affected by high salinity due to various factors, including low precipitation, high surface evaporation, weathering of native rocks, irrigation with saline water, and unsuitable agricultural practices (Jamil et al., 2011).

In the Niger River valley, clay soils, including vertisols, which are irrigated for rice production, are particularly vulnerable to salinization. These soils are increasingly irrigated due to their relatively high productive potential, primarily because of their high-water retention capacity and chemical fertility. However, the regular supply of irrigation water during the cropping season, combined with the low saturated hydraulic conductivity of clayey soils, limits salt leaching (Greve et al., 2010; Adam et al., 2012), causing salts to concentrate in the topsoil. During inter-cropping seasons, cracked soils allow salts to move from the soil matrix to prism walls, where they concentrate on the soil surface (Bouma, 1980). In the irrigated paddy perimeter of Kollo, Niger, the irrigation of vertisols raises the water table, which contains magnesium sulfate salts that accumulate in the topsoil due to evaporation, especially during the inter-cropping seasons. This salinization has led to the abandonment of paddy rice (*Oryza sativa*) plots in certain areas due to low yields (Adam, 2011). Ponding combined with surface flushing on these vertisols has shown that their low hydraulic conductivity when saturated limits the removal of salts, particularly from deeper layers (Adam et al., 2012).

Recent studies have shown that cultivating the fodder crop *Echinochloa stagnina* for 11 months improved the structure of these vertisols and significantly reduced the salt stock (SS) in both the topsoil and deeper layers (Ado et al., 2019). Given the poor performance of the paddy rice farming system on vertisols, it is essential to innovate with a more efficient cropping system that optimizes water use and ensures soil conservation by limiting salinization in the irrigated perimeter of the Niger River. Advanced technologies and innovation are vital for promoting sustainable food systems, as they can address critical challenges in transforming food systems and improving global food security and nutrition (Khan et al., 2021). A new agroecological approach for more sustainable paddy rice farming could be based on crop diversification or crop rotation, introducing crops like the fodder crop *E. stagnina*, known for its salt tolerance and high fodder productivity (Barbiero, 1995; Ado et al., 2016).

However, the dynamics of water and salt in these clayey soils under irrigated *E. stagnina* crops remain understudied. The key question is whether the cultivation of *E. stagnina*, by improving the hydrostructural properties of vertisols through its root system (as reported by Ado et al., 2019), can influence water and salt dynamics in these soils to limit salinization in the root zone. The main objectives of this study were to: (i) assess the influence of an *E. stagnina* fodder crop on the salt and water dynamics of vertisols compared to local practices of rice cropping in the irrigated perimeter of the Niger River valley, and (ii) test an agroecological approach for effective salt and water management to ensure better soil conservation and increase the productivity and sustainability of paddy rice farming systems developed on salt-affected vertisols in the Niger River valley.

MATERIALS AND METHODS

Study site

The study was conducted in the irrigated paddy fields of Kollo, located in the Niger River valley, 50 km southeast of Niamey, Niger (13° 16′ 35.32″ N, 2° 21′ 31.81″ E, Figure 1). The climate in the study area is Sahelian, characterized by an average annual rainfall of 700 mm, occurring over 4 months (June-September), and average monthly temperatures ranging from 25°C in December to 40°C in April. The soils at the study site are classified as acid saline vertisols (FAO, 2015; Michot et al., 2013) and have a high clay content (>70%), acidic pH (4.5-5.0), high electrical conductivity of soil saturated paste (13-29 dS/m), and very low saturated hydraulic conductivity (1.5-2.8 × 10^{-8} m/s) (Adam, 2011; Ado et al., 2016). The irrigated perimeter of Kollo has been cultivated with rice since 1980, following two cropping seasons per year: one during the rainy season (August-December) and the other during the dry season (February to May) (Adam et al., 2012).

Plant material

E. stagnina is a perennial semi-aquatic grass with C4 photosynthetic metabolism (François et al., 1989; Heuzé et al*.,* 2017). *E. stagnina* can grow up to 2.5 m in height, or even 10 m if it floats in water (Brink, 2006), and has a fasciculate root system that can quickly colonize the soil profile and create preferential water flow. Barbiero (1995) observed roots of *E. stagnina* up to 130 cm deep in silty clay soils of the Niger River valley and estimated its root biomass to be 35 to 40% of total plant fresh biomass. *E. stagnina* is likely to develop on saline and/or alkaline soils, but its tolerance thresholds for salinity and alkalinity are not yet known. *E. stagnina* is grown on submerged plots as a forage that has high nutritional quality (François et al., 1989; Charancle, 1994; Heuzé et al*.,* 2017).

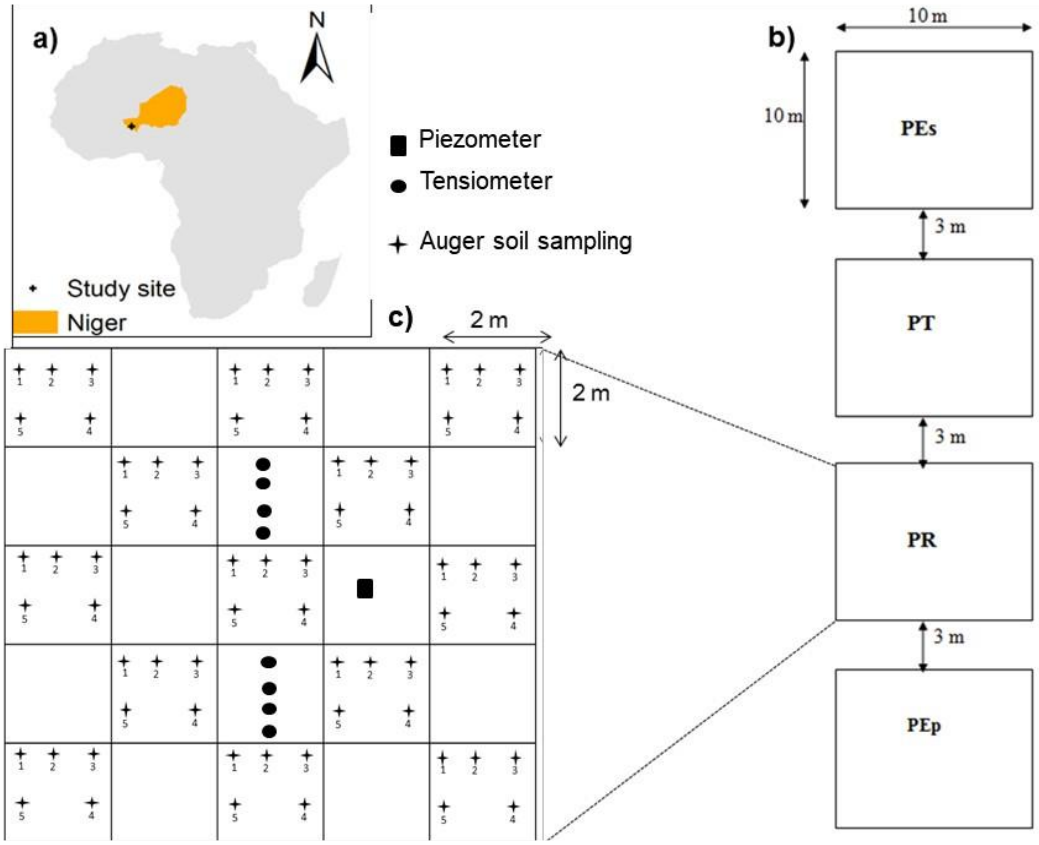


Figure 1. (a) Study site location, (b) experimental design and (c) soil sampling design for the four treatments: no crop (PT), rice crop (PR), seasonal *E. stagnina* crop (PEs) and permanent *E. stagnina* crop (PEp).

Experimental design

The experiment consisted of four treatments: (i) bare soil without crops, considered as the control (PT); (ii) soil cultivated with rice (PR) in two successive cropping seasons; (iii) soil cultivated with *E. stagnina* in two successive seasons (PEs) separated by a complete harvest; and (iv) soil permanently cultivated with *E. stagnina* (PEp), with staggered harvests throughout the experiment (Figure 1). The treatments were implemented in plots measuring 10 m × 10 m, separated by a 3 m alley, and bounded by bunds (0.4 m high × 0.5 m wide), surrounded by channels (0.4 m deep × 0.5 m wide) permanently filled with water to prevent water bypass from the plots (Figure 1). The plots were irrigated with water from the Niger River (electrical conductivity: 0.04-0.15 dS/m; pH: 6-8), pumped directly through PVC pipes using a Californian irrigation system.

Tensiometers (SDEC, 22 mm in diameter) were installed at depths of 20, 30, 60, and 80 cm, with two replicates per plot at each depth, to monitor the dynamics of the soil pressure head (Figure 1). The tensiometers were installed with a spacing of 50 cm × 50 cm per replicate in each plot. To monitor the dynamics of the water table, one piezometer was installed in each plot at a depth determined by the depth of the gravelly terrace (approximately 140 cm).

Crop production

Rice (“Gambiaka”” variety, 110-day cycle) and *E. stagnina* crops were cultivated over three successive cropping seasons, separated by two inter-cropping periods (IC1 and IC2), following the rice cropping calendar of the study area. After soil preparation in the plots, as per the method of Ado et al. (2016), rice plants and *E. stagnina* cuttings (about 20 cm in height with two nodes) were transplanted with spacings of 20 cm × 20 cm and 30 cm × 30 cm, respectively. The rice plants (Gambiaka variety, 110-day cycle) were first cultivated in nurseries for 3 weeks, while *E. stagnina* cuttings were collected from farmers' fields located in flood-prone areas of the Niger River Valley.

All plots were irrigated until the water level was 7 cm above the soil surface. The same irrigation strategy was applied throughout each cropping season: water from the Niger River was added weekly to maintain the water level at 7 cm above the soil surface. Inorganic fertilizers were applied during each cropping season in accordance with the doses and frequency outlined by Ado et al. (2016).

At the end of each cropping season in PEs and PR, the biomass and grain yields (both fresh and dry weights) were measured in two 2 m × 2 m subplots in each cultivated plot. For the permanent *E. stagnina* treatment (PEp), fresh and dry weight biomasses were measured at each bolting stage in two 2 m × 2 m subplots, and plant stubble was left at a height of 5 to 10 cm to allow for plant regeneration.

Monitoring of water dynamics

The static level of the water table was measured every 15 days in the piezometers using an electric probe. The soil-matric potential

(ψ_m) was also measured every 15 days at depths of 20, 30, 60 and 80 cm using a calibrated handheld electronic pressure meter with a hypodermic needle (SMS 2500S, SDEC France). The total hydric potential (ψ_T, hPa) was calculated at each measurement depth as the sum of soil-matric potential ψ_m and gravitational potential (ψ_g), using the soil surface as the reference level:

$$\Psi_T = \Psi_m + \Psi_g \quad (1)$$

At each ponding irrigation event, the amount of water supplied was estimated from the measured irrigation time and the flow rate of the irrigation motor pump. The depth of the water above the soil surface was measured at three locations per plot before each irrigation event to calculate a water balance for each plot during each cropping season.

Water use efficiency assessment

Water use efficiency (WUE) is one of the parameters used to evaluate the performance of irrigation system. WUE (kg/mm/ha) is generally defined as the ratio between the product (kg) and input water (mm) (van Halsema and Vincent, 2012):

$$WUE = \frac{\text{Product (kg)}}{\text{Input water (mm)}} \quad (2)$$

WUE was calculated at the end of each cropping season using the yield in fresh biomass under plots cultivated with *E. stagnina* (PEp and PEs) and the yields in fresh biomass and paddy grains under plot cultivated with rice. In addition, input water was summed from irrigation and rainfall per plot and per season to calculate WUE.

Soil sampling

To distribute soil sampling more evenly over space and time and minimize soil disturbance, each plot was subdivided into 2 m × 2 m subplots (Figure 1). Soil was sampled using a 3-cm-diameter gouge auger at four soil depths (0-10, 10-20, 20-40, and 40-60 cm) at the beginning and end of each cropping season. Composite soil samples representative of each plot were then created for each depth and each subplot row on each sampling date (Figure 1). Soil was sampled from staggered subplots (that is, every other subplot), resulting in a distance of approximately 60 cm between soil sampling locations within a given subplot over time (Figure 1). Twenty soil samples were collected per plot for each measurement date (that is, 80 samples from the four plots on each date). However, soil was not sampled at the beginning of S3 because this period coincided with the rainy season, during which the plots were permanently submerged, potentially influencing the analytical results of the soil samples.

Monitoring of salt stock in the soil

SS was monitored in the 0 to 10, 0 to 20, 0 to 40, and 0 to 60 cm soil layers using data from soil samples taken at the beginning and end of each cropping season. The electrical conductivity of a 1:5 diluted aqueous extract (EC1:5) of the soil samples was measured in the laboratory after filtering through a 2.5 µm filter, according to ISO 11265 (AFNOR, 1996). The salt stock (SS) (g/m²) was then estimated for each date across the four soil layers (0-10, 0-20, 0-40, and 0-60 cm) using measurements of soil dry mass and $EC_{1:5}$:

$$SS = \left[BD \times h \times \left(\frac{S_m}{M}\right)\right] \quad (3)$$

where BD is bulk density (g/cm^3), h is the thickness of the soil layer (m), S_m is the amount of salts in the soil sample (g) and M is the mass of the soil sample (g).

Bulk density was determined using the cylinder method at the end of each cropping season, but always under water-saturated conditions to limit the bias caused by Vertisol shrinking during drying. Soil moisture was estimated from an equation of Adam (2011):

$$S_m = 0.65 \times CE_{1/5} - 0.097 \quad (4)$$

Finally, the salt balance (ΔSS) was calculated at the end of the experiment as the initial salt stock (SSi) minus the final salt stock (SSf) in each of the four soil layers (0-10, 0-20, 0-40 and 0-60 cm):

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

Positive values of ΔSS for a given soil layer indicated salt removal and thus desalinization, while negative values of ΔSS indicated salt accumulation.

Data analysis

Linear mixed models (LMMs) were created (using the "lme4" package (Bates et al., 2016) of R software (R Core Team, 202X) to predict SS from the initial state to the end of S3 in each treatment in the four soil layers. LMMs are an extension of traditional linear regression models that were used to consider both fixed effects (α, β) related to time and random effects related to the treatment plot (α_i) to predict the relation between a response variable y_{ij} and covariates x_{ij} of repeated-measurement data that are grouped by a cluster factor:

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

where the random effects (α_i) related to the cluster factor follow normal distributions with zero mean and constant variance, and $\varepsilon_{i,j}$ is the real distribution of errors. Zuur et al. (2009) recommended using LMMs to decrease the bias of estimates based on repeated measurements, since correlations between observations can contribute to random effects. Pearson correlations were also calculated to identify significant ($P < 0.05$) relations between SS in the layers, the water table level, total soil potential measured at the four depths, cumulative water supply per season and a crop parameter (that is, fresh shoot biomass).

RESULTS

Dynamics of water input

The water added to the plots during the cropping seasons, primarily from irrigation, varied from 40 to 70 mm per date to maintain the water depth at 7 cm above the surface (Figure 2). Rainfall, which ranged from 1 to 60 mm per date, was observed only during the inter-cropping period (IC2) and the third cropping season (S3).

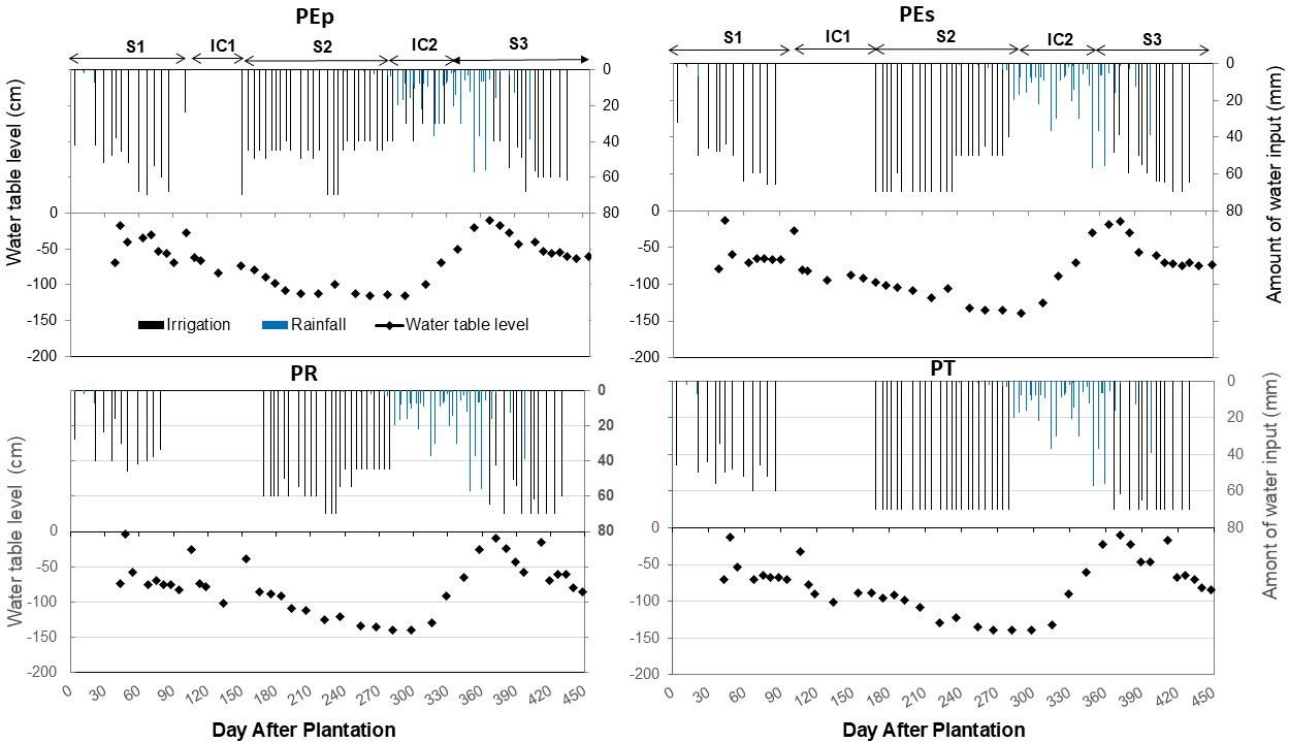


Figure 2. Dynamics of water input from irrigation (black bars) and from rainfall (blue bars) and the water table level (black diamonds) in the four treatments: no crop (PT), rice crop (PR), seasonal *E. stagnina* crop (PEs) and permanent *E. stagnina* crop (PEp). S1, S2 and S3 represent the three successive cropping seasons, respectively. IC1 and IC2 represent the first and second inter-cropping season, respectively, in PEs, PR and PT.

The frequency and amount of water supplied by irrigation were higher during S2 (the dry season) than during S1 and S3 (the rainy season). The cumulative water input was 1,420, 1,447, 1,332, and 1,672 mm during S2 for the PEp, PEs, PR, and PT plots, respectively, and 726, 782, 826, and 899 mm during S3, respectively. Notably, more water was applied to the PT plot
than to the cultivated plots, particularly during S2.

Water table dynamics

The fluctuation in the water table level closely reflected the dynamics of water supply to the plots through irrigation and rainfall (Figure 2). This fluctuation made it possible to distinguish three main periods:

i) 0 to 150 Day After Plantation (DAP), which coincides with cool and dry period in the area, the water table lay 40-100 cm deep. During this period, the water table was deeper (100 cm deep), which coincided with the end of S1, when irrigation was stopped for IC1. However, the water table occasionally rose when irrigation resumed after a period of drying, especially at the end of IC1.
ii) 150 to 270 DAP (March to June), the hot and dry season, when the water table lay 100 to 145 cm deep, especially in June, which coincided with IC2 in the PEs, PR and PT plots. In comparison, the water table level remained shallower in the PEp plot (100 to 120 cm deep), where the water supply was permanent, unlike in the other plots, which experienced IC2 (that is, no irrigation).
iii) 270 to 450 DAP (June-October), the rainy season and beginning of S3, when the water table rose to a depth of 10 to 40 cm.

After October, the water table tended to fall again, likely to resume a new cycle. Seasonal variations in rainfall and irrigation seemed to control the water table level. The water table was relatively shallower in the PEp plot than in the other plots, especially during IC2, which coincided with the dry season. Thus, the water table fluctuation is linked to both irrigation and crop system.

Change in hydric potential

Like the water table level, the total hydric potential fluctuated over time in all plots (Figure 3). The soil was wetter in the surface layer than in the deeper layers, and water flowed downward in all plots. During the cropping seasons, the total hydric potential ranged from -10 to -20 hPa at a depth of 20 cm and from -80 to -120 hPa at a

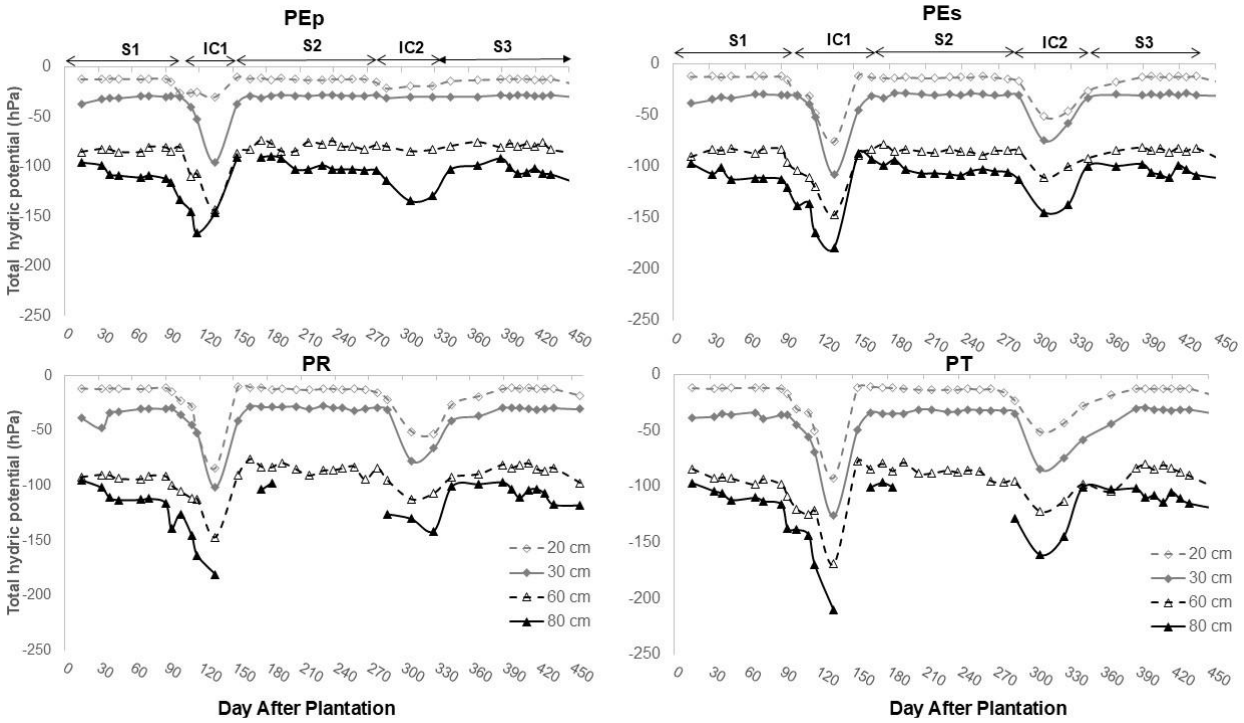


Figure 3. Dynamics of total hydric potential at depths of 20, 30, 60 and 80 cm in each treatment: no crop (PT), rice crop (PR), seasonal *E. stagnina* crop (PEs) and permanent *E. stagnina* crop (PEp). S1, S2 and S3 represent the three successive cropping seasons, respectively. IC1 and IC2 represent the first and second inter-cropping season, respectively, in PEs, PR and PT.

depth of 80 cm. However, during IC1 and IC2, the soil became drier at all depths and in all plots, except in the PEp plot at depths of 20, 30, and 60 cm, where the potentials remained relatively constant, especially during IC2. During the inter-cropping seasons, it ranged from 60 to -100 hPa at a depth of 20 cm and from -150 to -210 hPa at a depth of 80 cm in the PEs, PR, and PT plots. Moreover, the soil was drier at all depths and in all plots during IC1 (that is, the dry season) than during IC2 (that is, the beginning of the rainy season). During IC2, the total hydric potential tended to increase again, even before IC2 ended, especially at a depth of 20 cm, following the addition of rainwater. At deeper layers (60 and 80 cm), the soil tended to be drier in PT than in PEp, PEs, and PR, particularly during the inter-cropping seasons. Thus, the hydric potential was mainly controlled by soil moisture during the cropping seasons.

Salt stock dynamics

SS initially differed among plots, ranging from 630 to 812 g/m² in the 0 to 10 cm layer and from 3976 to 4910 g/m² in the 0 to 60 cm layer. It was higher in the PEp and PEs plots than in the PR and PT plots across all layers (Figure 4). SS decreased over time in all plots and all layers, with a more pronounced decrease in the plots cultivated with *E. stagnina* compared to the others. However, after IC1, SS was again higher at the beginning of S2 than at the end of S1 in all plots and layers, except in the PEp plot in the 0 to 20 cm layer, where it remained lower than on previous dates. In the 0 to 10 cm layer, SS became higher in the PT plot (645 g/m²) than in the other plots. For S3, SS was higher in the PR and PT plots than in the PEp and PEs plots across all layers, which was the opposite of what had been observed initially.

The LMMs predicted a significant ($p < 0.001$) decrease in SS from the initial state to S3 in all plots for the 0 to 10 cm and 0 to 20 cm layers (Figure 5). For S3, the LMMs indicated that SS was significantly higher in the PT plot than in the other plots in the 0 to 10 cm layer. In the thicker layers, particularly the 0 to 60 cm layer, the LMMs predicted that SS increased in the PR and PT plots but remained relatively stable or decreased slightly in the PEp and PEs plots. Thus, these results (Figures 4 and 5) demonstrate that changes in soil salt stock were influenced by *E. stagnina* crops, particularly in their ability to reduce the accumulation of SS in deeper layers more effectively than rice crops and the ponding technique.

Salt balance

After 15 months, the salt balance was positive in all

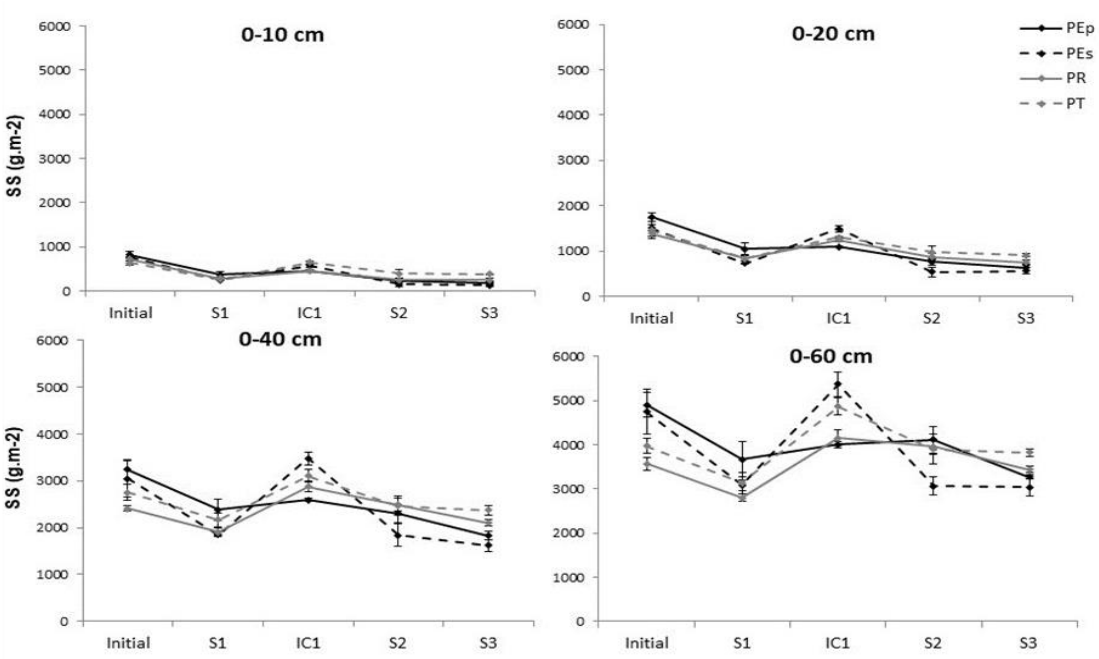


Figure 4. Salt stock (SS, $g.m^{-2}$) in the 0-10, 0-20, 0-40 and 0-60 cm soil layers by period and treatment: no crop (PT), rice crop (PR), seasonal *E. stagnina* crop (PEs) and permanent *E. stagnina* crop (PEp). S1, S2 and S3 represent sampling at the end of three successive cropping seasons, respectively. IC1 represents sampling at the end of the first inter-cropping season. The error bars represent 1 standard error (n=5).

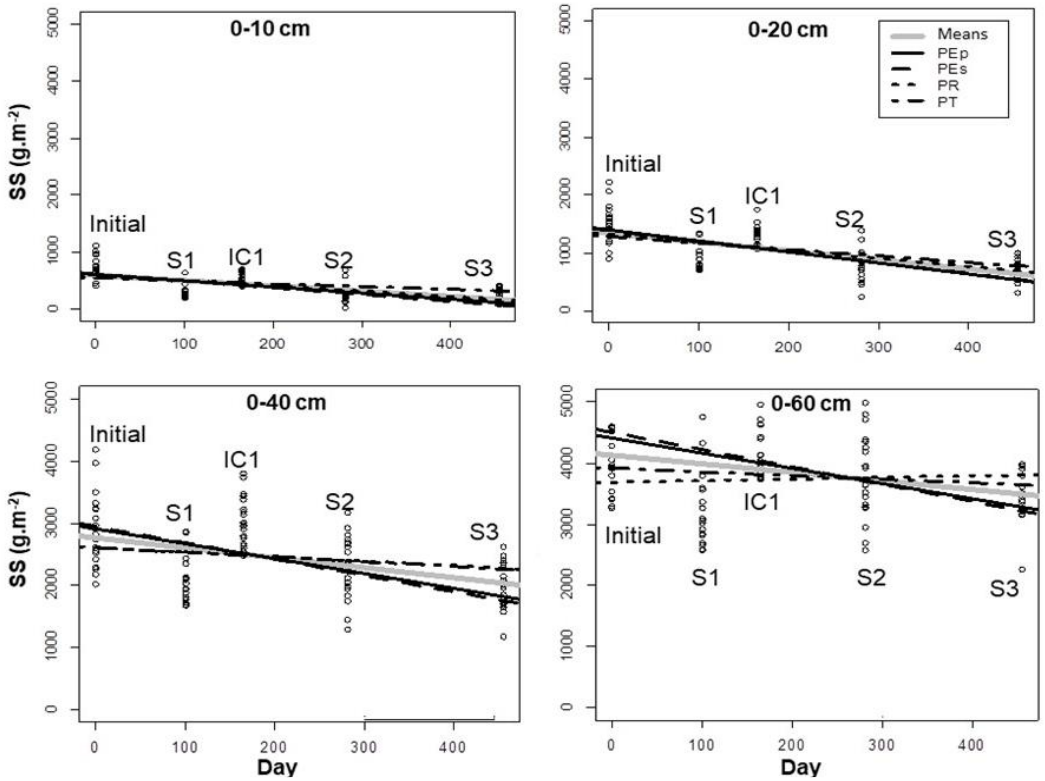


Figure 5. Linear mixed models of salt stock (SS) predicted at depths of 0-10, 0-20, 0-40 and 0-60 cm by treatment: no crop (PT), rice crop (PR), seasonal *E. stagnina* crop (PEs) and permanent *E. stagnina* crop (PEp). S1, S2 and S3 represent sampling at the end of three successive cropping seasons, respectively. IC1 represents sampling at the end of the first inter-cropping season.

Table 1. Amount of salts removed ($g.m^{-2}$) (and in parentheses, the percentage removed) from the 0-10, 0-20, 0-40 and 0-60 cm soil layers after 15 months, by treatment: no crop (PT), rice crop (PR), seasonal *E. stagnina* crop (PEs) and permanent *E. stagnina* crop (PEp).

Treatment	0-10 cm (%)	0-20 cm (%)	0-40 cm (%)	0-60 cm (%)
PEp	623.3 (*77*)	1112.3 (*64*)	1423.2 (*44*)	1635.8 (*33*)
PEs	633.6 (*83*)	937.5 (*62*)	1427.0 (*47*)	1713.6 (*36*)
PR	472.1 (*65*)	636.8 (*46*)	313.9 (*13*)	125.4 (*4*)
PT	249.1 (*39*)	551.3 (*38*)	371.8 (*13*)	145.8 (*4*)

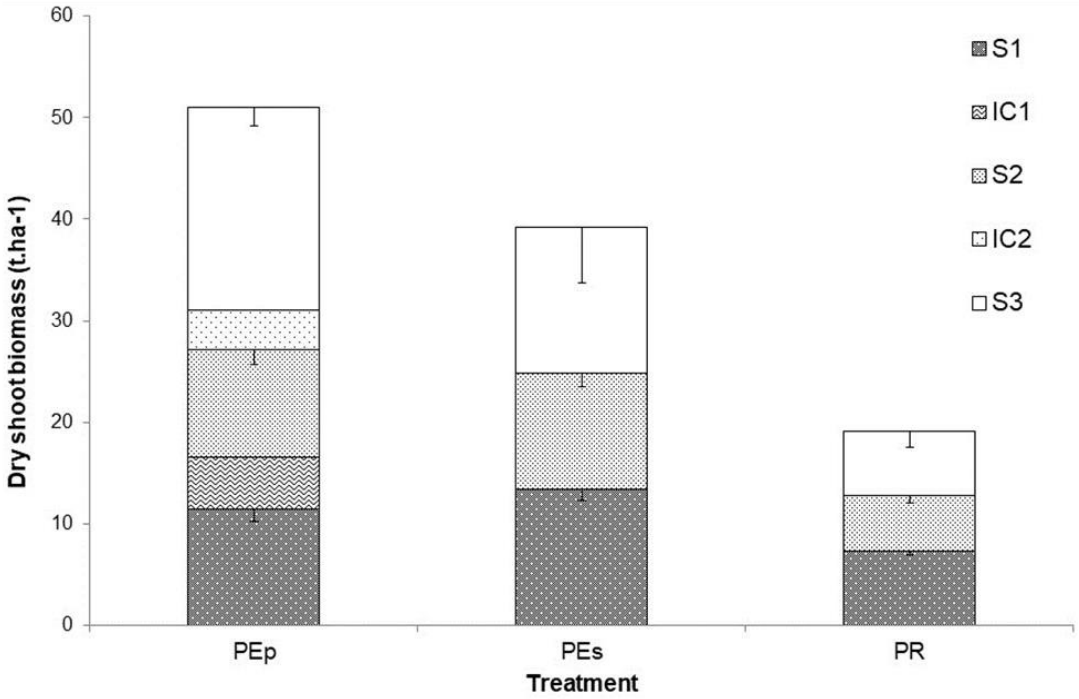


Figure 6. Dry shoot biomass ($t.ha^{-1}$) of *E. stagnina* and rice crops ($t.ha^{-1}$) by period and treatment: rice crop (PR), seasonal *E. stagnina* crop (PEs) and permanent *E. stagnina* crop (PEp). S1, S2 and S3 represent harvest at the end of the three successive cropping seasons, respectively. IC1 and IC2 represent biomass harvested at the end of the first and second inter-cropping season, respectively, in PEp.

treatments and soil layers, indicating a net loss of salts (Table 1).

More salts were lost in the PEp and PEs plots than in the PR and PT plots across all layers. In the surface layer (0-10 cm), the salt loss represented 77, 83, 65, and 39% of the initial SS in the PEp, PEs, PR, and PT plots, respectively. The amount of salt loss was 2.5 times greater in the PEp (623 g/m^2) and PEs (634 g/m^2) plots compared to the PT plot (249 g/m^2). In the 0 to 60 cm layer, the amount of salt loss represented 33 and 36% of the initial SS (that is, 1635 and 1714 g/m^2) in the PEp and PEs plots, respectively, while it represented only 4% of the initial SS in the PR (125.4 g/m^2) and PT (145.8 g/m^2) plots. Thus, the cultivation of *E. stagnina* decreased the SS of vertisols more effectively than rice cropping or simple submersion of bare soil.

Crop production

After 15 months, the crops produced 51, 39 and 19 t/ha of dry shoot biomass in the PEp, PEs and PR plots, respectively (Figure 6). Thus, the plots cultivated with *E. stagnina* (PEp and PEs) produced more dry shoot biomass than the rice plot (PR). The dry shoot biomass yield was higher at the end of S3 than at the end of S1or S2, especially in the plots cultivated with *E. stagnina*. In the PEp plot, the biomass measured at the end of S3 (20 t/ha) was twice as high as that at the end of S2 (10 t/ha) or S1 (11 t/ha). The grain yield of paddy rice in the PR

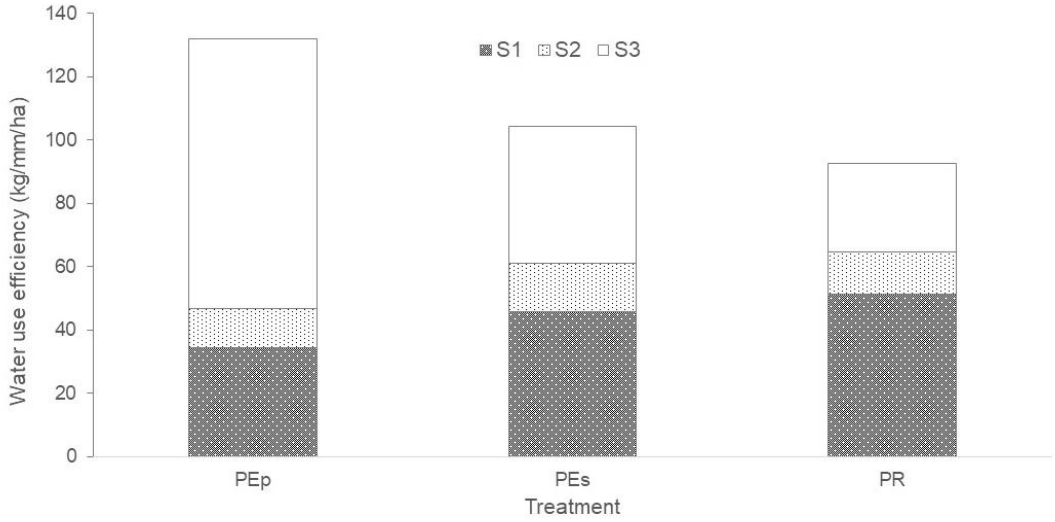


Figure 7. Changes in Water use Efficiency (WUE) according to cropping seasons and treatment. Rice crop (PR), seasonal *E. stagnina* crop (PEs) and permanent E. stagnina crop (PEp). S1, S2 and S3 represent sampling at the end of three successive cropping seasons, respectively.

plot remained relatively stable, at 5.0, 5.8 and 5.3 t/ha at the end of S1, S2 and S3, respectively.

Changes in Water use efficiency

WUE changes according to cropping season and treatments (Figure 7). Indeed, WUE is lower (12 to 15 kg/mm/ha) at the end of S2 (dry season) than that at the end of S1 (34 to 52 kg/mm/ha) and S3 (28 to 82 kg/mm/ha) (rainy seasons) in all treatments. Furthermore, WUE is higher under plots cultivated with *E. stagnina* (PEp and PEs) than that under the plot cultivated with paddy rice (PR) at the end of all cropping seasons except at the end of S1 where the opposite trend was observed. At the end of S3, WUE is 3 times higher under PEp than that under PR. Thus, *E. stagnina* crops optimize the use of water resources better than rice cropping system.

Relation between water dynamics and soil salinity in irrigated vertisols

The water table level was strongly correlated with soil salinity (SS) at depths of 20 to 40 cm and 40 to 60 cm (r = 0.56 and 0.64, respectively) (Table 2), but not with SS at depths of 0 to 10 cm or 10 to 20 cm. The water table level was also strongly correlated with the total hydric potential measured at all depths, except at 30 cm. The total water potential measured at 60 and 80 cm was also strongly correlated with SS measured at 20 to 40 cm and 40 to 60 cm. Irrigation was strongly correlated with the water table level (r = 0.90) and with the soil water potential measured at 20 cm (r = 0.66). However, the correlation between crop shoot biomass and SS was weak, regardless of the layer considered.

DISCUSSION

Influence of water irrigation on dynamics of the water table and salt stocks

Irrigation in the Kollo rice-growing area influenced fluctuations in the water table, total hydric potential, and dynamics of salts in the vertisols. The amount of irrigation was strongly and significantly correlated with the water table level (r = 0.90) and the soil hydric potential (r = 0.66). Furthermore, fluctuations in the water table level were strongly correlated with salt stock, especially in deeper layers (20 to 40 cm and 40 to 60 cm). These results confirm those of previous studies (Ducloux et al., 1994; Guéro, 2000; Adam, 2011) that found irrigation in Kollo accelerates the dissolution of salt-rich minerals and recharges the water table with saline solutes. However, the irrigation water in Kollo, drawn from the Niger River, has a low salt concentration (electrical conductivity of 0.040-0.015 dS/m) and positive residual alkalinity (Barbiero et al., 2001), indicating it poses little risk of causing soil salinization. As a result, the groundwater, which is stored among magnesium sulfate geochemical facies—where magnesium accounts for 70 to 85% of the cations and sulfate for 70 to 85% of the anions (Ducloux et al., 1944; Guero, 2000; Adam, 2011)—allows salts to concentrate in surface layers due to evaporation and the very low saturation hydraulic conductivity of vertisols. The influence of the water table on soil salinity has also been reported in several studies (Ceuppens et al., 1997;

Table 2. Pearson correlation matrix for all periods combined between the cumulative water supply per season (Irrig.) (mm), soil water properties, electrical conductivity (saturated paste extract (EC, dS/m) at four depths, salt stock (SS, g/m^2) in seven soil layers, fresh shoot biomass of the crops (Biom, t/ha), static water table level (NS, cm) and total soil potential (ψt, hPa). Bold text indicates strong correlations ($r \geq 0.50$).

SS_{010}	SS_{1020}	SS_{2040}	SS_{4060}	SS_{020}	SS_{040}	SS_{060}	NS	Ψt_{20}	Ψt_{30}	Ψt_{60}	Ψt_{80}	Biom	Irrig
1													
0.80	1												
0.78	0.79	1											
0.35	0.28	0.67	1										
0.95	0.94	0.83	0.34	1									
0.91	0.91	0.95	0.52	0.96	1								
0.83	0.80	0.96	0.75	0.86	0.95	1							
0.13	0.12	0.56	0.64	0.13	0.35	0.46	1						
0.34	0.28	0.62	0.69	0.33	0.49	0.59	0.88	1					
-0.01	0.07	0.10	0.47	0.03	0.07	0.21	0.34	0.52	1				
0.34	0.43	0.53	0.65	0.40	0.49	0.59	0.61	0.78	0.78	1			
0.42	0.32	0.60	0.71	0.39	0.52	0.62	0.74	0.93	0.50	0.69	1		
-0.32	-0.24	-0.34	0.19	-0.30	-0.33	-0.18	-0.19	0.02	0.58	0.33	0.11	1	
0.03	0.01	0.43	0.54	0.02	0.23	0.33	0.90	0.66	0.34	0.523	0.49	-0.25	1

Samba, 1998; Houk et al., 2006; Northey et al., 2006; Ndiaye et al., 2008; Li et al., 2015), which found that (i) irrigation during cultivation raises the water table, often loaded with salts, and (ii) evaporation during inter-cropping periods allows salts to concentrate in surface layers. Thus, the inter-cropping period plays an important role in concentrating salts in the root zone of soils, as reported by Ndiaye et al. (2008).

Impact of an *E. stagnina* crop on dynamics of salt stocks of vertisols

The cultivation and irrigation of *E. stagnina* in the rice-growing area of Kollo significantly decreased the salt stock in the vertisols. After 15 months, the salt stock decreased by 77, 83, 65, and 39% in the PEp, PEs, PR, and PT plots, respectively, in the 0 to 10 cm layer. This amount of salt loss was 2.5 times greater in the plots cultivated with *E. stagnina* (PEp and PEs) than in the submerged bare soil (PT). In the 0 to 60 cm layer, the decrease in the initial salt stock was 33 to 36% (that is, 1635-1714 g/m²) under *E. stagnina* crops compared to only 4% under rice cropping (125.4 g/m²) or simple submergence of bare soil (145.8 g/m²). Compared to submerging bare soil and then draining surface water (Adam et al., 2012), cultivating *E. stagnina* decreased the salt stock of vertisols more effectively in both the surface and deeper layers (Figure 8). Adam et al. (2012) found that submerging vertisols to decrease salt stocks through leaching and/or flushing was effective only for the surface layer due to their very low saturation hydraulic conductivity, which limits the mobilization of salts. Moreover, the results of the present study agree with those of previous studies that indicated that cultivating *E. stagnina* decreased the salinity of salsodic clay soils after two years of cultivation in Egypt (Helalia et al., 1992) or the alkalinity of silty-clay soils in the Niger River valley after one year of cultivation (Barbiero et al., 2001). The decrease in soil salinity by salt-tolerant crops or halophytes has been reported in several studies (Qadir et al., 2007; Rabhi et al., 2010; Zorrig et al., 2012; Zhao et al., 2013). This reduction in soil salinity by *E. stagnina* is related to the leaching of salts (a major process), which is promoted by the improvement of soil structure through the plant's roots (Ado et al., 2019) and the uptake and accumulation of salts by plant biomass (Zhao et al., 2013; Ado et al., 2016).

Fodder crop of E. stagnina improve water use efficiency of salt-affected vertisols

Cultivating *E. stagnina* in the irrigated perimeter of Kollo not only decreased the salt stock in the root zone of vertisols but also improved water use efficiency for fodder production on these long-abandoned saline soils. This study demonstrated that *E. stagnina* can grow on saline vertisols and produce 39 to 51 t/ha of dry fodder after 15 months, with a yield of 10 to 20 t/ha of dry biomass per cutting. Similar studies have also observed the capacity of forage plants to provide production on saline soils (Qadir et al., 2008; Rabhi et al., 2010). The yields observed in this study are comparable to those noted in the Niger River valley, which range from 10 to 30 t/ha of dry matter (Dieter and Hassane, 2001), but are higher than those obtained from saline-sodic clay soils in Egypt (13 t/ha/year of dry matter) where no fertilizer was

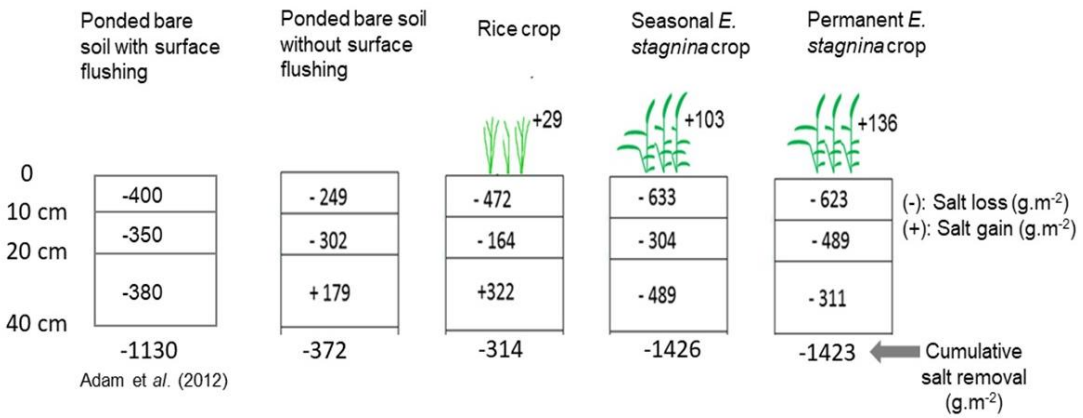


Figure 8. Summary of the decrease or increase in salt stock (g m^{-2}) observed in soil layers by Adam et al. (2012) and those observed in crop biomass and soil layers for the four treatments studied in the present study: no crop (PT), rice crop (PR), seasonal *E. stagnina* crop (PEs) and permanent *E. stagnina* crop (PEp).

applied (Helalia et al., 1992). *E. stagnina* is known for its high nutritional quality (François et al., 1989; Heuzé et al., 2017) and is locally used for livestock feed, making it of economic interest to farmers. Furthermore, the results of this study indicated that water use efficiency (WUE) is higher with *E. stagnina* than with rice crops. WUE is three times greater in the PEp plot than in paddy rice crops at the end of S3, highlighting the effectiveness of the irrigation system for producing *E. stagnina* fodder on salt-affected vertisols in the irrigated perimeter of Kollo. These results confirm *E. stagnina*'s capacity to tolerate saline soil and ensure fodder production while optimizing water consumption compared to rice crops, as reported by various authors (Barbiero, 1995; Helalia et al., 1992; Ado et al., 2016). Thus, introducing *E. stagnina* fodder crops in the irrigated perimeter of Kollo may serve as an alternative solution to i) decrease soil salinity in saline vertisols, ii) improve water use efficiency, and iii) promote the diversification of agricultural production within this irrigated rice paddy system for soil conservation. This agro-ecological practice can enhance the performance of this irrigated system concerning agricultural production, as well as soil and water conservation. This approach represents a promising pathway to maintain the sustainability of this irrigated rice paddy system over time in the semi-arid context of Niger.

Conclusion

This study demonstrated that irrigation influences the dynamics of water and salts in vertisols within the paddy perimeter of Kollo in the Niger River valley, both under fodder crops of *E. stagnina* and under rice crop production. Fluctuations in the water table, primarily induced by water inputs, were strongly correlated with the salt stock, particularly in deeper layers. However, there were processes of capillary rise of salts during intercropping seasons. The irrigated *E. stagnina* crops decreased soil salinity by reducing the salt stock by 33 to 36% in the 0 to 60 cm soil layer, compared to only 4% under rice cropping or submerged bare soil at the same depth. Moreover, water use efficiency (WUE) was higher with *E. stagnina* crops than with rice crops. WUE was three times greater in the PEp plot than in paddy rice crops at the end of S3, highlighting the effectiveness of the irrigation system for producing *E. stagnina* fodder on salt-affected vertisols in the irrigated perimeter of Kollo. The introduction of *E. stagnina* fodder crops into the cereal rotation appears to be a promising agro-ecological strategy for promoting vertisol desalinization while simultaneously diversifying agriculture. To complement this study, future research could focus on the geochemical processes linked to salt dynamics and water table fluctuations, as well as the capacity of other local crops with high economic potential to tolerate the conditions of salt-affected vertisols, thus facilitating crop diversification and maintaining the sustainability of the irrigated system in the Niger River valley.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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