Sustainable management of coastal saline soils in the Saloum river Basin, Senegal

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ABSTRACT

Salinization of soils is one of the major environmental problems facing the world. Frequent tidal intrusions and continuous decrease of annual rainfall support the salinization of soils in the coastal area of the Saloum river Basin, West Central of Senegal, West Africa. This study aimed at appreciating the spatial variability of soil salinity along a levee to backswamp toposequence in the Saloum River basin; in order to assess the constraints and potentialities of these saline soils and propose sustainable soil management strategies. One transect (2.2 km) oriented East-West, including 9 soil profiles located on three topographic units: floodplain, low terrace, and middle terrace was selected. Soil chemical properties (electrical conductivity, pH, water soluble cations and anions) were analysed to estimate the salinity level at each soil horizon (n = 45). Soil pH (3.5-8.5), electrical conductivity (0.01-55 dS m^{-1}) and water-soluble cations (Na$^+$, K$^+$, Ca^{2+}, Mg^{2+}) and anions (Cl$^-$, SO$_4^{2-}$) decrease with altitude. The study demonstrates the close correlation between landscape position and soil salinity illustrated by a two-dimensional salt distribution pattern: horizontal and vertical. The horizontal pattern is appreciable at landscape scale and supports different salinity level between the three topographic positions. The vertical pattern occurs within soil profiles and is closely linked to soil texture and groundwater dynamic. The topographic position exerts thus the major influence on soil salinity along the toposequence. Mulching appears ultimately as the most efficient method in reclaiming these coastal saline soils.
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Keywords: soil salinity, soil management, Saloum river basin, Senegal, West Africa

INTRODUCTION

Soil salinization is one of the main problems in arid and semiarid regions (UNEP, 1991). It reduces soil quality, limits the growing of crops, constrains agricultural productivity and, in severe cases, leads to the abandonment of agricultural soils (Amezketa, 2006; Acosta et al. 2011). Salinity problems are caused from the accumulation of soluble salts in the root zone. These excess salts reduce plant growth and vigor by altering water uptake and causing ion-specific toxicities or imbalances. High salt concentrations can induce osmotic stress in plants and lead to the toxic accumulation of ions, such as Cl$^-$ and Na$^+$ (Hasegawa et al., 2000; Maathuis, 2006), particularly in the surface soil horizons (Ohrtman et al., 2012). Establishing good drainage is generally the cure for these problems, but salinity problems are often more complex (Bauder et al., 2014). Worldwide, more than 800 million hectares of land are estimated to be salt-affected (FAO, 2008), and approximately 10% of the Earth's

total land surface may be salt-affected (Schofield and Kirkby, 2003). These soils cover a range of soils defined as saline, saline–sodic and sodic (Ghassemi et al., 1995). Even though the general assumption is that salt-affected soils occur primarily in arid and semiarid climates, these soils are actually found in every climatic zone in every continent except Antarctica (Rengasamy, 2006, 2010). In Australia, concern has risen over salinization and the accompanying decline of riparian vegetation in many of their floodplain systems (Holland et al., 2006; Costelloe et al., 2008), with an insufficient understanding of groundwater–surface water interactions cited as the primary factor currently hampering management (Lamontagne et al., 2005). Increasing salinity has also been implicated in the loss of large areas of *Acacia xanthophloea* (fever tree) woodlands in south and east Africa (Mills, 2006; Humphries et al. 2011). Salt accumulation in shallow groundwater systems has been observed in a range of wetland environments, including the swamps of the Okavango Delta, Botswana (McCarthy et al., 1993); the Pantanal, Brazil (Barbiero et al., 2002); prairie wetlands in North America (Arndt and Richardson, 1993); and Australian floodplains (Salama et al., 1993; Jolly et al., 1993). Many of the parameters relevant to salinization processes are related to elevation and landscape position. These include rainfall, vegetation, soils, geology, geomorphology and farming practices (tree clearing and ploughing). These have all affected surface shape and runoff patterns. In addition, groundwater levels often correlate well with topography (Salama et al., 1993), causing salinity to occur in low areas, convergent areas and at breaks of slope (Dowling et al., 2003). Although soil salinity is recognized as a major limitation to cropping and the focus of many plant breeding efforts to produce salt-resistant crops, generally, it is neglected as a factor in plant ecology, except in the ecology of deserts (salt pans and playas) and wetlands (salt marshes, mangroves) where its importance is obvious given the prevalence of halophytes (Bui, 2013). Evaluating the spatial variability of basic soil properties in saline soils, and mapping the spatial distributions of these soil properties, can help farmers and agricultural managers make effective site-specific management decisions (Zheng et al., 2009).

The coastal region of West Central Senegal is a low – lying land raising only a few meters above sea level. This situation allows seawater to flow as far as 100 km inland through the main channels and into the estuaries of tidal rivers, particularly the Saloum River. The intrusion of seawater results, in this particular zone, in the formation of saline soils, which render the land unfit for agricultural production. The area affected by this kind of salinization is estimated to be as large as one million hectares (Fall, 2010), and is continuously expanding. Previously confined on lowlands (floodplain, low terrace), saline soils are now identified on all landscape positions, including arable uplands (middle and high terraces) (fall, 2010). Soils in this coastal area have been subject to some research in the past. Sène and Matty (2014), Faye et al. (2014) and Thiam et al. (2015) analysed their agronomic and forestry potentialities for soil-management purposes. Fall (2010) and Fall et al. (2014) studied the genesis and mineralogy of saline acid sulphate soils (ASS) in the Saloum river Basin for sustainable land use and management. But these studies have seldom been oriented on sustainable soil management strategies for efficient land use. In the present study the spatial variation of soil salinity on different landscape positions along a levee to backswamp toposequence in the coastal area of the Saloum River Basin, west central of Senegal was investigated in order to assess the constraints and potentialities of these soils and propose sustainable soil management strategies.

MATERIALS AND METHODS
Field measurements and site factors
The Saloum River Basin (13°35' - 14°30'N and 16°00' - 16°50'W), with about 250.000 ha, belongs to the transitional region between Sahelian and Sudanian zones of West

Central Senegal. The distance of the investigated toposequence is 2.2 km. The sampling transect is oriented East-West and runs across the estuary (Figure 1). It has a general slope of 0.5%.

Topography was determined using a theodolite (Fall, 2010). According to the WRB (FAO, 2006), soils were described in January - February 2007 and April - May 2008, during the dry season. Spatial variability of soil properties was explored through 9 soil profiles along the toposequence; three on the floodplain, as well as on the low terrace and the middle terrace. They are a good cross-section of regional soil genesis and development pattern. Electrical conductivity (EC) and pH values were first estimated in the field with field EC and pH-meters (WTW, 8120 - Weilheim, Germany) before a repetition in laboratory under standard conditions. Groundwater level (GWL) was daily estimated with a measuring tape, during the dry season (January-February, 2007 and March-April, 2008) through 42 piezometers (Fall, 2010).

Laboratory work

Samples were dried at room temperature. Particle-size distribution was performed after organic matter removal with H_2O_2 and excessive salts removal by repeated addition of deionised water, centrifugation and decantation until the EC dropped to ≤ 40 µS/cm (Schlichting et al., 1995). After subsequent addition of NH_3 for water dispersion, overnight shaking and ultrasonic treatment, the sand fractions were obtained by wet-sieving, while the silt and clay fractions were separated by pipette analysis after Köhn (Schlichting et al., 1995).

The soil pH was measured in a 0.01 M $CaCl_2$ solution and water (1:2.5 by weight, 10 g air dry soil mixed with 25 ml deionised water) and determined with a pH-electrode. The electrical conductivity (ECe) was measured on solutions extracted by centrifugation of 1:5 soil–water (20 g air dry soil in 100 ml deionised water) mixtures (Schlichting et al., 1995).

The water-soluble cations (Na^+, Ca^{2+}, Mg^{2+}, and K^+) and anions (Cl^-, SO_4^{2-}) were measured in 1:20 soil-water extracts and determined using flame photometer (ELEX 6361, Natheler + Hinz GmbH, Hamburg, Germany) for Na^+, Ca^{2+}, and K^+; atomic absorption spectroscopy (AAS; Perkin Elmer model 3100, Perkin-Elmer GmbH, Überlingen, Germany) for Mg^{2+}; and ion chromatography (Dionex 2000i, Dionex, Sunnyvale, CA) for Cl^- and SO_4^{2-}. Cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) and anions (Cl^- and SO_4^{2-}) were thereafter individually presented to assess their abundance at two different depths: 0-30 cm and 30-60 cm. This depth corresponds with the root zone of the investigated profiles. The method used assumes that the available cations or anions in the sample sum to 100% and the individual cation is a fraction of the total. Other anions, mainly NO^{3-}, CO_3^{2-}, PO_4^{3-}, were excluded from this estimation; they were either not detectable or show trace amounts in all samples. All soil analyses were performed in duplicate on the fine earth fraction (< 2 mm). Results are expressed on the basis of the oven-dry (105 °C) soil weight. Graphics were performed using the Excel software, 2013.

A Scanning Electron Microscope (SEM) (LEO 420; LEO Electron Microscopy Ltd, Cambridge, UK) equipped with a field emission cathode and coupled to an Energy Dispersive X-ray (EDX; INCA 400 system, Oxford Instruments, Abingdon, UK) was performed in the fine earth fraction to confirm the mineral composition in some selected samples.

RESULTS
Variation of soil salinity along the toposequence

Soil salinity was investigated through the ECe and the water-soluble cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, SO_4^{2-}). Values of ECe, Na^+ and Cl^- (respectively the dominant cation and anion) increase seaward; with a maximum obtained in the floodplain profiles (ECe ≤ 55.5 dS m^{-1}, $Na^+ \leq 33.2$ cmol c+kg^{-1}, $Cl^- \leq 37.7$ cmol c+kg^{-1}). With ECe $\leq$ 10 dS m^{-1}, $Na^+ \leq 2.8$ cmolc+kg^{-1}, and $Cl^- \leq 5.5$

$cmolc+kg^{-1}$, appear low terrace soils less saline than floodplain soils, but more saline than the middle terrace soils (ECe ≤ 2.5 dS m^{-1}, Na+ ≤ 0.007 cmol $c+kg^{-1}$, Cl- ≤ 0.09 cmol $c+kg^{-1}$) (Table 1).

Floodplain soils

Water soluble cations occur in the floodplain soils in the following order of abundance: $Na^+ > Mg^{2+} > Ca^{2+} > K+$, and anions in this order: $Cl^- > SO_4^{2-}$ (Figure 2). Sodium (Na^+) and Chloride (Cl-) dominate hence in the cation and anion pools, respectively; this reflects their marine origin on this lowest landscape position. They show similar distribution trend as ECe, with the highest values in the top- and subsoil, traducing the influence of the shallow saline groundwater table and the surface salt crusts. Magnesium (Mg^{2+}) is the second most abundant water soluble cation present in the floodplain soils; it remains almost stable with depth. Calcium (Ca^{2+}) and potassium (K^+) decrease appreciably with depth (Figure 2). Chloride remains also nearly constant within floodplain profiles, except for the topmost horizons (Az, Azm, and Ahz for P1, P2, and P3, respectively) where it decreases slightly at the expense of sulfate (SO_4^{2-}) (Figure 2).

Low terrace soils

Water soluble cations occur in the low terrace soils in the following order of abundance: $Na^+ > Mg^{2+} >$ or $< Ca^{2+} > K^+$, and anions in this order: $Cl^- > SO_4^{2-}$ (Figure 2). Values of Na^+ and Cl^- remain the most abundant in soils on this intermediate landscape position. They decrease with altitude, being lower throughout P6 compared to P4 and P5; but increase altogether with depth, traducing the groundwater influence. The previous order of cation availability noted in the floodplain soils is somewhat altered by the predominance of Ca^{2+} relative to Mg^{2+} throughout profiles, mainly P6 (Figure 2). Except for the subsoil of P4, important values of Ca^{2+} and Mg^{2+} were obtained. This important abundance of Ca^{2+} and Mg^{2+} reflects the acid conditions of low terrace soils. Under such conditions, the base cations are replaced by acid cations (mainly H^+ in the studied soils) and normally leached out of the system. Their presence supports, therefore, restricted leaching process due to the presence of clayey subsoil material in these profiles. Anions show a similar order of abundance as in the floodplain profiles: $Cl^- > SO_4^{2-}$, with SO_4^{2-} increase and Cl decrease in the topsoil of soil profiles (Figure 2).

Middle terrace soils

Water soluble cations and anions show their lowest values in the middle terrace profiles (Figure 2). This supports the absence of marine influence coupled with a nearly complete leaching of salts during the rainy season on this highest landscape position. The abundance order of cations is represented as follows: $Na^+ ≥ K^+ ≥ Ca^{2+} ≥ Mg^{2+}$. So apart from an important increase of Na^+ in the subsoil of P8 and P9, cations seem in better equilibrium in the middle terrace soils compared with the other topographic positions (Figure).

Salinization of soils in this coastal area is caused by the intrusion of hypersaline water from the Atlantic Ocean through tidal inundations and capillary rise from a shallow saline groundwater. The intensity of tidal inundations decreases uplands, while the groundwater depth increases in the same direction. The floodplain soils appear therefore more saline relative to the low terrace and the middle terrace soils.

Apart from having a high salt content, salt-affected soils show also considerable diversity in their biological, physical, chemical, mineralogical and micromorphological characteristics. Salts precipitate at the surface or accumulate in the soil profile as diverse minerals (Wongpokhom et al., 2009; Bui, 2013). Halite (NaCl) remains the most abundant salt mineral in the studied soils. It shows a seaward increase and well-structured crystals in some soil aggregates from the floodplain (Plate 1a) and low terrace (Plate 1b) profiles. Preference was given to the topsoil of soil profiles marked by the presence of salt crusts resulting from the intense evaporation of the saline groundwater.

Table 1: Selected soil properties of the study sites.

Depth (cm)	Horizon	Colour	Texture (%)			pH		EC dS m^{-1}	Water soluble Ions (cmol$_{c+}$ kg^{-1})					
									Cations				Anions	
			Sand	Silt	Clay	CaCl$_2$	H$_2$O		Na$^+$	K$^+$	Ca^{2+}	Mg^{2+}	Cl$^-$	SO$_4^{2-}$
Floodplain (P1), Gleyic Hyposalic Solonchak (Sulphatic), 14° 04' 27.4'' N / 016. 11' 17.4'' W														
0-1	Az	7.5Y4/1	24.5	56.7	18.8	8.2	8.4	26.5	10	0.2	1	2.4	14.5	1.4
1-4	Bjz	7.5YR5/6	25.6	37.4	37	7.8	7.9	11	4.7	0.1	0.3	0.9	5.6	0.5
4-23	Bjv	7,5YR4/2	17.9	34.8	47.2	6.1	6.1	12	5.2	0.1	0.2	0.9	5.7	0.3
23-60	Bv	10YR3/3	29.4	31.4	39.2	4.5	4.5	15.5	7	0.1	0.2	1.2	8.2	0.4
Floodplain (P2), Gleyic Hypersalic Solonchak (Sulphatic), 14° 04' 23.8''N / 016. 11' 16.6''W														
0-1	Azm	5Y3/1, 5YR5/8	22.8	45.7	31.5	7.8	7.9	55.5	33.2	0.3	2	5.1	37.7	2.6
1-8	Az	2.5Y4/1	27.6	32.9	39.4	7.8	8.0	9	3.8	0.2	0.3	0.9	4.3	0.4
8-30	Cjr	2.5YR3/1 10YR7/6	21.3	30.7	47.7	7.3	7.5	8.5	4.2	0.1	0.2	0.7	4.5	0.3
30-60	Cr	7.5YR2/2	42.3	30.5	27.2	5.0	5.0	14	6.5	0.1	0.2	1.9	7.8	0.4

Floodplain (P3), Gleyic Hyposalic Solonchak (Sulphatic), 14° 04' 21.4'' N / 016. 11' 06.0''W

0-5	Ahz	7.5YR5/4	75.2	21.6	3.2	7.6	7.8	12.5	4.2	0.08	1.4	1.5	5.5	1.4
5-11	Cz	10YR7/2	69.8	25.9	4.3	7.0	7.3	7	2.4	0.06	0.6	0.7	2.5	0.7
11-17	C	10YR6/4	79.5	17.8	3.1	6.2	6.5	5.5	1.4	0.05	0.6	0.4	2	0.6
17-26	Bl1	7.5YR5/8	83.6	10.7	6.1	5.4	5.5	5.5	2	0.06	0.3	0.5	2.3	0.2
26-34	Bl2	Mottled	78.9	12.2	8.8	6.2	6.3	7	3	0.07	0.4	0.7	3.8	0.2
34-70	Bhr	7.5YR2/1	64.3	11.0	24.7	6.2	6.2	16	7.3	0.2	0.4	1.5	7	0.5

Haplic Gleysol (Thionic), 14° 04' 19.4'' N / 016. 10' 59.2''W

0-2	Ah1	7.5YR3/3	57.2	26.4	16.3	4.0	4.1	0.5	1.7	0.02	0.6	0.6	2.3	0.2
2-16	Ah2	10YR4/4	57.9	18.3	23.7	4.8	5.0	2.5	0.1	0.004	0.003	0.001	0.08	0.03
16-38	Bl1	7.5YR4/3	61.8	18.3	20	4.2	4.5	4.5	0.2	0.006	0.01	0.01	0.1	0.03
38-62	2Bl2	10R4/3	45.8	23.3	30.9	4.2	4.3	7.5	0.3	0.006	0.02	0.02	0.3	0.03
62-90	2Bl3	5Y6/1	46.0	21.3	32.7	4.5	4.5	9.5	0.4	0.008	0.03	0.03	0.4	0.04
90-100	2Brl	2.5Y5/2	41.8	23.6	34.6	4.9	4.7	1	0.4	0.01	0.03	0.03	0.4	0.04

Low Terrace (P5), Haplic Gleysol (Thionic), 14° 04' 20.3''N / 16. 10' 59.5''W

| 0-2 | Ahz1 | 10YR3/3 | 70.4 | 19.7 | 9.7 | 4.5 | 4.4 | 1 | 2.8 | 0.1 | 0.9 | 2.2 | 5.5 | 0.2 |
| 2-11 | Ahz2 | 10YR3/4 | 62.5 | 18.3 | 19.1 | 3.9 | 3.9 | 0.5 | 1.2 | 0.07 | 1.8 | 1.2 | 3 | 0.5 |

11-29	Bwz	10YR4/6	46.7	22.4	31	3.8	3.9	4.5	1.1	0.06	0.3	0.9	2.4	0.04
29-51	Bl1	2.5YR4/6	50.0	21.4	28.6	3.7	3.7	3	0.8	0.04	0.2	0.6	1.6	0.03
51-81	Bl2	2.5Y6/2	48.7	21.3	30	3.8	3.9	2.5	0.7	0.03	0.2	0.3	1.1	0.03
81-100	Brl	2.5Y6/2	38.6	22.9	38.3	4.0	4.1	2	0.7	0.03	0.1	0.2	1.5	0.04

Low Terrace (P6), Haplic Gleysol (Thionic), 14° 04' 21.2''N / 016. 10' 51.6''W

0-4	Ahz	10YR2/3	82.1	12.8	5.1	5.9	5.9	10	2.2	0.01	1.6	1.4	5.4	0.09
4-32	Ahlz	10YR2/2	67.6	21.8	10.5	4.4	4.4	6	1.2	0.008	1	0.8	3	0.06
32-62	Bl1	10YR4/6	71.0	20.0	8.8	4.0	3.9	5	0.9	0.005	0.8	0.7	2.6	0.04
62-82	Bl2	10YR5/6	68.6	17.2	14.3	3.9	3.8	4	0.7	0.004	0.8	0.7	2.1	0.03
82-110	Brl	10YR4/6	61.7	12.4	26	3.8	3.7	5.5	1.9	0.006	0.8	0.8	2.8	0.03

Middle Terrace (P7), Endogleyic Arenosol, 14° 04' 15.9''N / 016. 10' 47.5''W

0-26	Ap	10YR3/4	85.1	9.7	5.1	4.1	4.7	0.01	0.001	0.002	0.001	0.0004	0.002	0.001
26-60	Ah	10YR3/4	79.8	1.0	6.2	4.2	4.7	0.04	0.001	0.001	0.001	0.0004	0.002	0.001
60-108	Cw	7.5R8/3	90.4	8.6	0.8	4.6	5.3	0.02	0.0002	0.001	0.001	0.0001	0.002	0.001
108-160	Bl	7.5YR7/4	88.4	9.7	1.8	4.9	5.4	0.03	0.0004	0.001	0.001	0.0002	0.002	0.001

Middle Terrace (P8), Endogleyic Arenosol, N 14° 04' 14.0'' / W 016. 10' 47.1''

0-31	Ap	10YR2/2	77.6	15.3	7.1	4.6	4.9	0.03	0.001	0.001	0.001	0.001	0.002	0.001
31-62	AhC	10YR3/2	78.8	18.3	3	5.2	5.7	0.03	0.001	0.001	0.001	0.001	0.002	0.001
62-107	1Cw	7.5YR7/3	82.1	15.9	2	5.6	6.0	0.03	0.0004	0.001	0.001	0.001	0.002	0.001
107-138	2Bl	10YR6/3	72.9	10.7	16.4	5.8	5.8	0.20	0.007	0.002	0.002	0.002	0.004	0.002
138-160	1Bl	10YR8/2	83.5	12.5	4.3	6.0	6.4	0.05	0.001	0.001	0.0005	0.0002	0.002	0.002

Middle Terrace (P9), Endogleyic Arenosol, 14° 04' 14.0''N / 016. 10' 47.2''W

0-36	Ap	10YR2/3	67.5	18.2	14.3	5.8	6.0	0.15	0.001	0.001	0.001	0.001	0.003	0.001
36-67	Ah	10YR3/3	64.6	20.3	15.1	6.2	6.5	0.10	0.002	0.002	0.002	0.002	0.002	0.001
67-88	Cv	10YR4/3	70.1	17.4	12.5	6.7	7.6	0.30	0.002	0.002	0.001	0.002	0.004	0.002
88-126	Bc	10YR5/4	64.9	20.5	14.6	6.8	7.8	1.00	0.002	0.002	0.003	0.003	0.03	0.002
126-160	Bl	2.5Y3/2	61.4	14.5	24.1	6.5	6.8	2.50	0.002	0.002	0.006	0.005	0.09	0.003
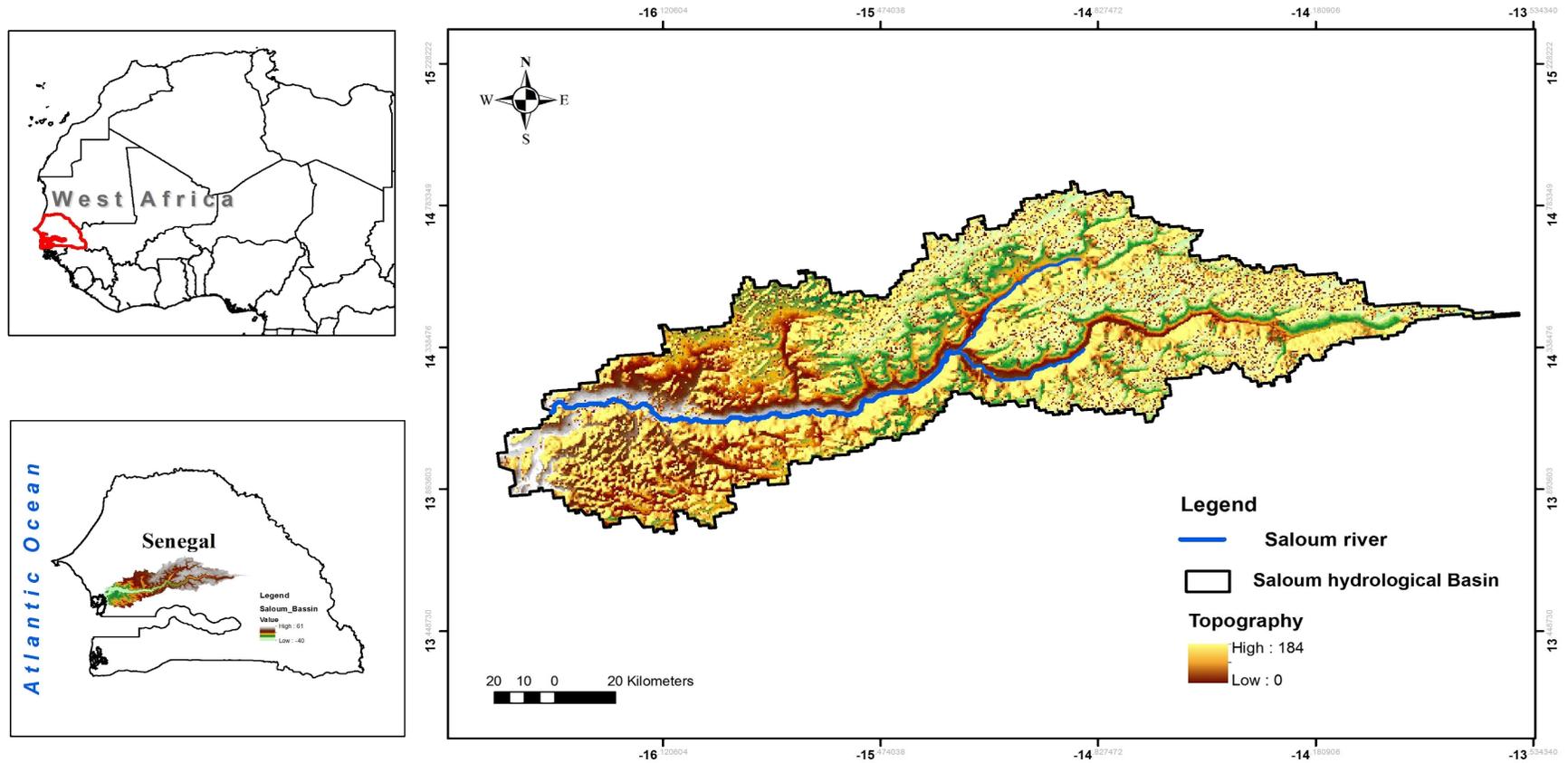
Figure 1: Location Map on the Saloum river basin, West Central Senegal, West Africa.
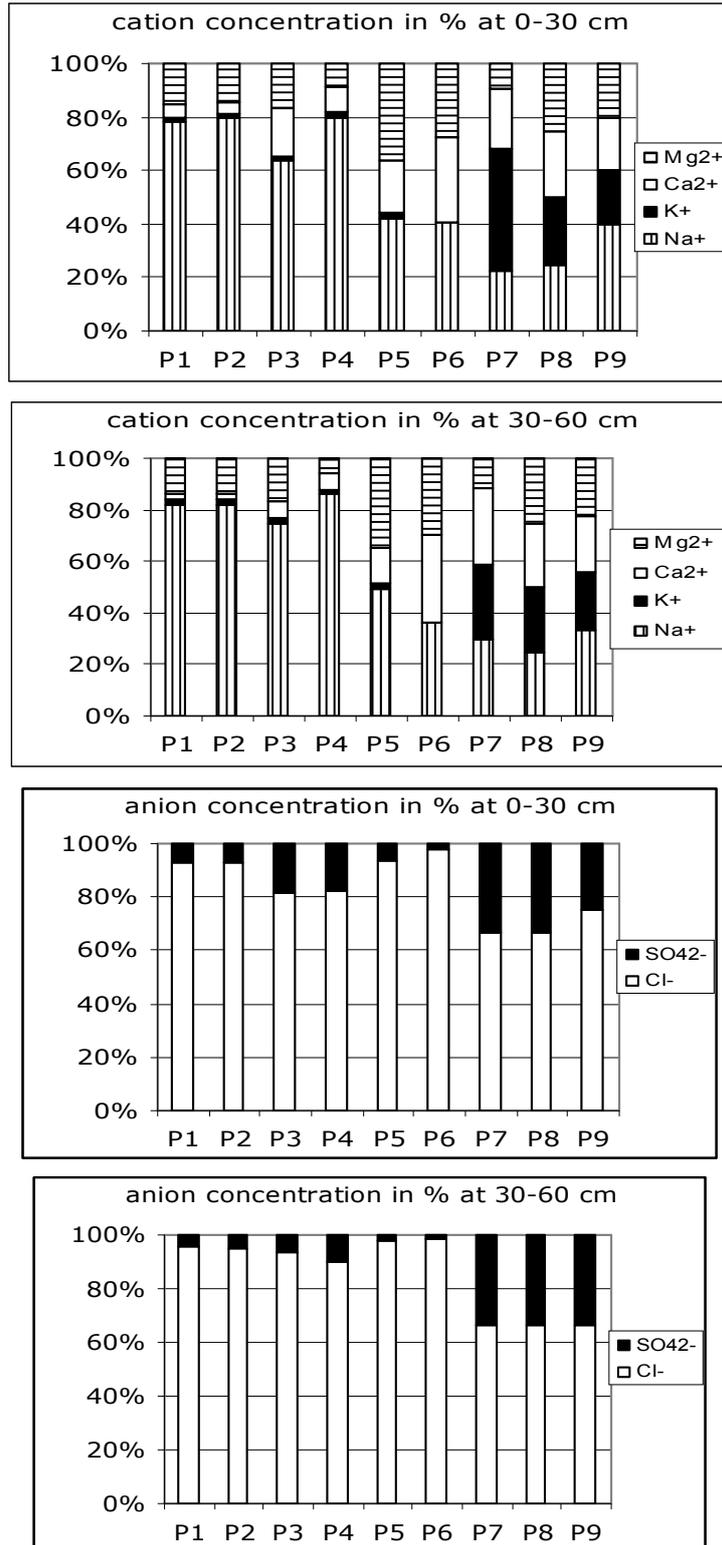
Figure 2: Mean values of water-soluble cations (Na^+, Ca^{2+}, Mg^{2+}, and K^+) and anions (Cl^-, SO_4^{2-}) at 30 cm and 60 cm depth.
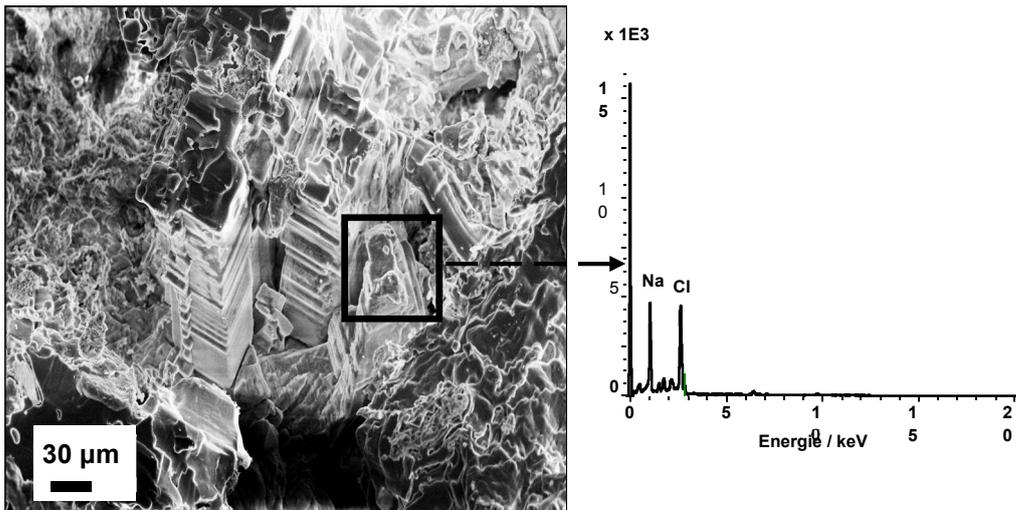
Plate 1a: Floodplain
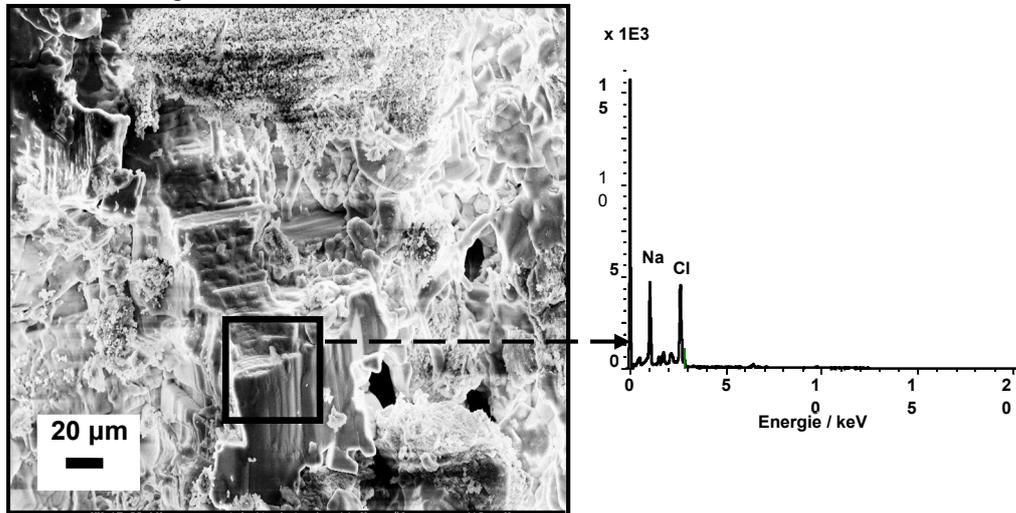
Plate 1b: Low terrace

Plate 1: SEM and EDX showing Halite crystals in the floodplain (P2: Gleyic Hypersalic Solonchak (Sulphatic); Azm/Az horizons: 0-8 cm) and low terrace (P5: Haplic Gleysol (Thionic); Ahz1/Ahz2 horizons: 0-11 cm).

DISCUSSION
Salinization process in the Saloum river Basin

Despite considerable research on coastal saline soils worldwide, the adverse effect of salinity still prevails and poses greater challenges to manage them. Our study demonstrates the close correlation between landscape position and soil salinity illustrated by a two-dimensional salt distribution pattern: horizontal and vertical. Both salt distribution patterns act concurrently with variable intensity according to the landscape position and the season. This variation, common process in coastal plains, reflects a significant dynamic of salts in saline areas (Bresler et al., 1984; Boivin, 1984; Daffé and Sadio, 1988; Sadio, 1991; Hussein and Rabenhorst, 2001).

The horizontal pattern is appreciable at landscape scale and supports differences in soil salinity between the three topographic positions: floodplain, low terrace and middle terrace. It is determined by the characteristics of the site and the impact of tidal flooding. Because frequency and intensity of tidal flooding increases with decreasing altitude, the floodplain soils contain more soluble salts than low terrace and middle terrace soils. The vertical pattern occurs within soil profiles and is closely linked to soil texture and groundwater dynamic. Depending on the soil texture, the relative water and salt content, and osmotic pressure of the saturation extract can be very different (US Salinity Laboratory, 1969). Soil texture remains therefore an important physical parameter contributing to accentuate vertical salinization processes. It may explain the high salinity of floodplain soils. The fine and nearly homogeneous texture of these soils supports less permeability and thereby promotes continuous upward fluxes of the saline groundwater. As shown by Vieillefon (1977) and Marius (1982), tidal and recently-reclaimed sulphidic soils have large concentrations of soluble salts as a result of prolonged flooding by seawater. We attributed the vertical salt distribution pattern within the low terrace profiles to the presence of texture-contrast soils (TCS), with sandy loam upper layers and silty clay sublayers, which determine the annual depth of the water table and the extent of the evaporation front. Rose et al. (2005) demonstrated in laboratory experiments the high concentration of salt in the particular zone between the soil surface and the water table in sandy loam texture, and explained it by the presence of a discontinuity in saline soil profiles of arid and semi-arid regions. It happens when the evaporative demand is greater than the ability of the soil to conduct water in the liquid phase. The lowest salt concentration was detected in the middle terrace soils. These soils present a sandy texture throughout all profiles. They are under continental influence and seldom face the marine intrusions. It is known that where the

sites are at higher elevation and only rarely inundated by seawater, the rate of salinization is expected to be low, as a result of nearly complete leaching of salts during the rainy season.

The impact of seawater in soil properties is well demonstrated in the above analysis. Soils in our toposequence are conspicuously marked by marine actions whether through tidal flooding (horizontal pattern) or water table fluctuations (vertical pattern). They bring water and soluble salts considered as soil genesis factors in this coastal environment. As a result, high salinity of marine water seems to have an important impact on soil genesis in the Saloum river Basin. As related by many authors, the presence of soluble salts in the sediments influences considerably soil formation and development. Maymard and Combeau (1960), Michel (1973), Faure et al. (1980) and Deckers et al. (1997) stated that the last transgression, which started about 2000 years ago, was responsible for incorporation of marine salt into the sediments in which the soils of the coastal area of Senegal have formed. Consequently, the sequence of transgression–regression cycles is thought to have had a great influence on soil formation in the Senegal valley (Barbiero et al., 2005). The influence of marine intrusions appears, therefore, decisive on soil formation in this area. Sadio (1991) suggested, for this reason, that despite their seasonal and spatial variation, salts more soluble than gypsum have to be regarded as an important factor of soil genesis in arid tropics coastal areas, and therefore have to be considered as soil classification criteria.

Mulching as the most efficient method to reclaim saline soils in the Saloum river basin

Although salinity has adversely affected agriculture for thousands of years, the recognition that salt-affected land can be used for agriculture is relatively recent. Interest in the use of saline land resources has escalated

over the last 20 years (Ghassemi et al., 1995; Bennett et al., 2009). Many approaches have been attempted to counteract the soil salinization process in the Saloum river Basin. The construction of small dams (mechanical approach) in order to stop saline water from the riverbed was experimented in the 1960-1970s. The biological approach consisting in the use of salt-tolerant plants (*Tamarix sp., Eucalyptus sp., Melaleuca sp., Prosopis sp....*) to reclaim saline soils was tested before. This approach is being attempted in a few places of the basin. The limited success of both methods separately applied leads to a new bio-mechanical approach based on the use of salt-tolerant plants (*Tamarix Aphylla, Atriplex lentiformis; Distichlis spicata*), combined with soil ridges surrounding the field to prevent rainwater from running off. The rational behind this combined approach is that it might be possible, through the massive planting of Tamarix trees, to lower the saline water table in the salt affected area. As a result, rainwater could replace the evacuated soil volume and in the process leach the salts from the upper soil layers. This method could be successful in the context of saline soils coupled with a long rainy season facilitating a well leaching process. But it can be harmful in the Saloum river Basin characterized by low annual rainfall and severe acid conditions.

Soil management strategies in this part of Senegal, and coastal West African areas at large, have thus to take into account the complex interactions between salinity and acidity. Because lowering the water table creates aerobic conditions on the topsoil, which leads to the oxidation of pyrite present in soil sediments. The oxidation of pyrite gives rise to severe acidity, which renders these soils of little value for agriculture. Also if promoting a high water table, as suggested by some authors, seems a practical way to avoid pyrite oxidation and soil acidification, it should be realised that maintaining a high water table is not advisable in many areas of the Saloum river Basin; the presence of saline groundwater at shallow depths (rooting zone) could be detrimental for plant growth.

The present study shows a vertical gradient of salt movement consisting in alternating bottom-up (capillary rise of groundwater towards the soil surface) and top-down (infiltration of soluble salts from the seawater). So, any technique that would stop or hinder the capillary rise of groundwater and salt concentration on the top layers of soil profiles is required. The use of surface-applied or incorporated straw mulches to reduce the strong evaporative demand of the atmosphere could be a practical way. Mulching is the most cost effective means of soil protection in the plant production, because of a range of positive effects on the soil fertility and other factors important for plant production (Shelton et al., 1995). Moreover, mulch improves soil conditions, especially reduces water evaporation from soil and helps maintaining stable soil temperature (Ji and Unger, 2001; Kar and Kumar, 2007). The cover of mulch influences soil moisture as well (Ramakrishna et al., 2006). Mulch maintains stable soil moisture, especially in surface soil layer (Dvořák et al., 2011). As a consequence of reduced evaporation, soil mulching benefits the conservation of water, particularly in the topsoil, decreases the evapo-concentration of the salts present in the irrigation water and the soil solution (Zhang et al., 2008), and minimizes soil salinization and sodication (Chaudhry et al., 2004; Rahman et al., 2006; Aragüés et al., 2014). Likewise, Singh et al. (2016) investigated long-term effects of tillage on crop yield and physicochemical properties of sodic soils and conclude that continuous tillage and cropping can be useful for physical and chemical restoration of sodic soils. Mulch could maintain the water table at rational depth and promote higher moisture in the topsoil by reducing the vapour flow out of the soil profile. The net result is a relatively greater downward movement of water and salt in mulched soil than in bare soil (Carter and Fanning, 1964). As a consequence, mulching of soil surface reduces evaporation losses and salt build-up in the topsoil. Also, lowering the aeration rate in the topsoil avoids the

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oxidation of pyrite and subsequent soil acidification. Grigg et al. (2006) observed in laboratory study, that mulch application improved infiltration, increased soil moisture retention and reduced surface crust strength. In the field, mulches incorporated to a depth of 0.15 m at application rate at least 20 t ha^{-1} straw or 80 t ha^{-1} sawdust were needed to mitigate capillary rise of salts during drying cycles and support satisfactory vegetation cover. Rosicky et al. (2006) used different methods: ridging, mulching and liming; to reclaim acid sulphate soil scalds of some costal floodplains of New South Wales, Australia. They found that mulching was the most important single treatment; it minimised significantly the build-up of surface salinity in dry times.

Mulching appears, therefore, very efficient in reclaiming saline soils present in the Saloum river basin. It requires, however, scientific investigation of soil properties before any application. Beye (1973) applied the mulching method to reclaim saline acid soil in the coastal area of southwestern Senegal and obtained up to 50% reduction of salinity in the topsoil (around 30 cm) after four years despite low rainfall during the trial period. But the lack of soil characterization makes these results really transient, limiting their large-scale application. Accordingly, Grigg et al. (2006) suggested further research in order to ascertain the long-time efficiency of the mulching technique.

Conclusion

Previous research in the coastal area of the Saloum river Basin attributed the soil salinization processes to the severe drought of the 70s involving a fall of water table and the topographic setting which determines the impact of seawater intrusions. Nevertheless, they fail to investigate the salt distribution pattern at landscape scale and within soil profiles. Our results demonstrated the two-dimensional salt distribution pattern and the influence of water table and soil texture in the dynamic of soil salinity. Soil management strategies in this part of Senegal have also to take into account the interactions between

salinity and acidity. Because lowering the water table creates aerobic conditions on the topsoil, which leads to the oxidation of pyrite present in the sediments of this coastal area. Also, maintaining a high water table in order to control pyrite oxidation is not advisable in many areas of the Saloum river Basin. The presence of saline groundwater at shallow depth could be harmful to plant growth. The mulching technique appears as the most sustainable soil management strategy in this coastal environment. It may reduce soil salinization by lessening the strong evaporation demand and subsequent formation of surface salt crust. It may also limit soil acidification in promoting relative soil moisture in the upper horizons of soil profiles.

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