Improving Pearl Millet (*Pennisetum glaucum* (L.) R.Br.) Productivity in Salt-affected soils in Senegal: A Greenhouse and Field investigation

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Abstract

The primary soil limitations to crop yield in the Senegalese "Peanut Basin" include salinity, acidity, and fertility. Crop yield may be increased by use of soil amendments and salt-tolerant cultivars. Objectives of this research were to evaluate salt tolerance of various millet (*Pennisetum glaucum* (L.) R.Br.) cultivars and compare effects of soil amendments on millet growth and yield in greenhouse and field studies. The research included two greenhouse experiments (i) comparing the salt tolerance of seven pearl millet cultivars (IBMV 8402, SOSAT C88, ICMV-IS 88102, IKMP1, IKMP2, IKMV 8201 and GAWANE) using five levels of electrical conductivity (0.3. 2.1, 4.2, 5.2 and 6.3 dS m^{-1}) and (ii) assessing SOSAT C88 responses to various organic (compost and peanut shells) and inorganic (phosphogypsum; PG) amendments in manufactured saline soils (4.2 dSm^{-1}); and (iii) a two-year (2014-2015) field experiment in Senegal evaluating the effects of local organic amendments (peanut shells and compost) on the responses of three millet cultivars (SOSAT C88, GAWANE and IBMV 8402) under low and high soil salinity. Cultivars SOSAT C88 and IBMV 8402 performed best in saline greenhouse media. The soil amendments that elicited the best millet plant responses in the greenhouse experiment were yard waste compost and peanut shells. Phosphogypsum exacerbated salinity effects by increasing electrical conductivity. In the field study, there were no differences among treatments. Cultivars IBMV 8402 and SOSAT C88 could be cultivated in saline soils amended with peanut shells.

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1. Chapter I: Introduction

1.1. Problem description

In Senegal, arable lands represent 19% of the total country area, which is about 3.8 million ha, but the actual area cultivated annually is 2.5 million ha (ANSTS, 2011). Only 2% of this area is irrigated, mostly in the north in the Senegal River basin, and the remaining agricultural land is rain-fed. The exploitation rate of the arable lands is greater in the "Peanut Basin" (81%); however, and the loss of arable land in this part of the country, coupled with the decrease of crop yield, is due primarily to soil salinity.

Salinity is a critical issue in soils adjacent to estuaries and at low elevation. Each year, Senegal loses thousands of ha of farm land due to salinization. About 1,230,000 ha are salt-affected soils. The consequences of this land degradation are mainly (i) desertion of rice fields, (ii) decrease in soil fertility and biodiversity, (iii) rural population exodus, (iv) food security decrease, and (v) increased poverty (ANSTS, 2011). In the Peanut Basin, where peanut and millet are the main crops, soil conditions are characterized by a moderate electrical conductivity (4 dS m^{-1}) that is not favorable for some cropping systems. This land deterioration is caused by biophysical (marine transgression, tidal movements, capillary rise of saline groundwater, transportation and deposition of salt particles by wind) and biotic (deforestation and extensive agriculture) factors. These factors are amplified in the "Bassin Arachidier" (or "Peanut Basin") by a rainfall deficit (Figure 1.1) and a Senegalese population explosion (Figure 1.2) that reached 14.6 million people in 2014 (FAOSTAT, 2016).

Figure 1.1. Peanut Basin of Senegal (in green). Source: ISRA 2010.

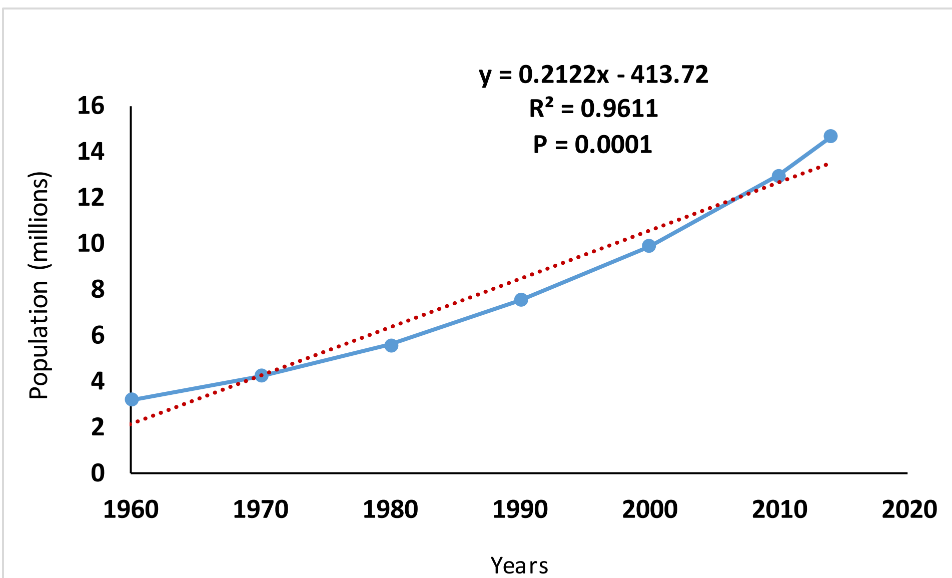

Figure 1.2. Senegalese population from 1960 to 2014. Source FAOSTAT, 2016.

As a result, saline lands have steadily increased in many parts of the Peanut Basin, gradually reducing cereal compatible arable land. Soil salinization has become a grave concern that limits the use of thousands of ha of farmland in Senegal (Sadio, 1991), especially in the regions of Saint-Louis, Kaolack, Fatick, Thies, and Ziguinchor. In the specific case of Sine Saloum, where our experiment is sited, the main cause of soil salinization is sea water intrusion from the Sine and Saloum Rivers as a result of repetitive droughts accompanied by a saline water table that rises to within 1-2 meters of the soil surface and concentrates salts at the surface by evaporation. The deterioration of natural resources by the phenomenon of land salinization has caused profound socio-economic and biophysical changes in this area and the worsening climate and human activities have undermined the balance of local ecosystems and production systems (e.g. endemic methods of cultivation and use of resources).

Some strategies (construction of anti-salt dikes and the adoption of crop management best practices) have been developed to alleviate the salinity in order to improve millet productivity in the Fatick region. The use of organic amendments and some millet cultivars tolerant to salinity could also be beneficial to both plant growth and yield increase.

1.3. Objectives

This research project was aimed at integrating aspects of soil management, organic amendment strategies and millet cultivars to fit the cropping systems of local farmers. A field study in Ndoff (Senegal) was combined with a laboratory and greenhouse investigation at Virginia Tech (Virginia, USA). The following were the overall objectives of the study:

1. To identify pearl millet cultivars tolerant to salinity in a greenhouse study;
2. To determine amendment effects on pearl millet responses in both greenhouse and field studies;

1.4. Hypotheses

1. H_0: An increase in salinity will not lead to a decrease in plant growth and yield

   H_1: Plant growth and yield will be decreased by an increase of salinity

2. H_0: The decrease rate in growth and yield due to salinity will be the same for all millet cultivars.

   H_1: At least one millet cultivar will be less affected by salinity (tolerant).

3. H_0: Organic amendments will not improve millet growth and yield in salt-affected soils.

   H_1: Organic amendments will ameliorate millet growth and yield in saline soils.

4. H_0: Organic amendments will not affect soil physical and chemical properties.

   H_1: Soil physical and chemical properties will change due to organic amendments.

2. Chapter 2: Review of Related Research

The population of Senegal in 2013 was 13.5 (ANSD, 2014). A great challenge facing Senegal is feeding a growing population where arable land is decreasing due to soil acidity, low fertility and salinity. Two types of agriculture that occur in Senegal include familial small plot farming, which is dominant in the country (98% of cultivated areas), and industrial, which comprises only 2% of the farms.

2.1. Familial agriculture

Senegal's agriculture is dominated by small farmers (family-type) who are dependent on rainfall for moisture. There are three categories of familial agriculture in Senegal (FAO, 2014). The first category is slightly equipped with production resources (i.e., lands, seeds, fertilizers) with a high rate of indebtedness and their needs coverage (food supply) is no longer than 3 months. This represents 20% of the familial holders. The second category, moderately equipped with production resources, constitutes 68% of the farmers. In this intermediate position, the production can sustain farm family needs for 3 to 12 months. The last category, which is well equipped with production resources, represents only 12% of familial agricultural lands. These farmers are able to produce food that exceeds their needs for more than one year. This is concordant with the findings of Cisse et al. (2004), who analyzed the economic agricultural production in the Senegalese Peanut Basin. They reported that poverty was severe in their area of the study (Thies and Diourbel), large farms were not as poor as small farms, and non-farm income is necessary for poverty alleviation. The total contribution of the small farmers to the Senegalese market is 67% of total agricultural production. However, not all this production is food or major cereals.

The main cereals grown in Senegal are millet, sorghum (*Sorghum Bicolor* (L.)), maize (*Zea mays* (L.)), paddy rice (*Oryza glaberrima* Steud.) and fonio (*Digitaria exilis* Stapf). The land area, total production and yields for each cereal in 2013 are presented in Table 2.1 (DAPSA, 2016). These values vary annually depending on the rainfall and seed availability.

Table 2.1. Area, production and yield of the five principal cereals in Senegal in 2013

	Area (ha)	Annual Production (Mg)	Yield (Mg ha^{-1})
Millet	741,208	572,155	0.8
Sorghum	106,500	97,501	0.9
Maize	151,450	223,234	1.5
Paddy Rice	108,227	423,482	3.9
Fonio	1,554	1,030	0.6

2.2. Major Constraints of the Agricultural sector in Senegal

Growing crops in Africa, particularly in the sub-Saharan regions of the continent, is challenging due to limited soil productivity caused by low nutrient availability, salted-affected soils (Table 2.2.) and soil acidity (Okorogbona, et al., 2015). These factors also limit agricultural productivity in the Peanut Basin of Senegal.

2.2.1. Soil Salinity

Traditionally, soil salinity has been assessed using soil samples collected from the root zone and averaged over time and depth. It is usually measured via laboratory analysis as electrical conductivity of a saturated soil paste extract (ECe) which was developed. Soil paste extract method was developed by USSL (1954). Soil samples wetted to saturation, allowed to equilibrate, and extracted under vacuum for collection of solution for EC measurement. This method of measuring salinity provides a direct relationship with the field moisture range for most soils, but there are other less complicated methods. Soil to water suspensions of 1:1, 1:2, 1:5 or 1:10 ratios are more easily performed than saturation extracts. A soil is saline if the saturated paste EC of the soil solution is greater than 4 dS m^{-1} (Soil Survey Staff, 1975). Thresholds of different categories of salt-affected soils are defined in Table 2.2.

Table 2.2. Types of salt-affected soils base on their electrical conductivity, sodium adsorption ratio and exchangeable sodium percentage.

Types of soil	Electrical Conductivity (EC) dS m^{-1}	Sodium Adsorption Ratio (SAR)	Exchangeable Sodium Percentage ESP
Saline	> 4	< 13	< 15
Sodic	< 4	> 13	> 15
Saline-sodic	> 4	> 13	> 15

Notes: The EC method involves preparing a saturated soil paste by stirring, during the addition of distilled water, until a characteristic endpoint is reached. A suction filter is then used to obtain a sufficient amount of the extract for making the conductivity measurement with an EC meter. ESP identifies the degree to which the cation exchange complex is saturated with sodium. Equation 1 shows how it is calculated. SAR gives information on the comparative concentrations of Na^{+}, Ca^{2+}, and Mg^{2+} in soil solution and is calculated as shown by equation 2.

$$ESP = \frac{\text{Exchangeable sodium, cmol}_c\ \text{kg}^{-1}}{\text{Cation exchange capacity, cmol}_c\ \text{kg}^{-1}} * 100 \qquad \textbf{Eq. 1}$$

$$SAR = \frac{[Na^{+}]}{(0.5\,[Ca^{2+}] + 0.5\,[Mg^{2+}])^{1/2}} \qquad \textbf{Eq. 2}$$

High salinity is a significant threat to agricultural productivity in numerous arid and semiarid regions throughout the world (Qadir, et al., 2000) as plant growth may be severely affected at conductivity values lower than those categorized as saline. The Terminology Committee of the Soil Science Society of America proposed to lower the boundary level of EC between saline and non-saline soils to 2 dS m^{-1} (Table 2.3) (Bohn, et al., 1985) because sensitive plants are affected at conductivities around that level (Nachtergaele, 2001). Ali, et al. (2004) identified soil salinity stress as the most serious environmental problem that decreases crop growth rate, crop development and crop yield in arid and semi-arid regions of many parts of Africa. Salinity also reduces the availability of animal feeds in arid and semi-arid regions of the world by decreasing the growth rate or production of grassland cover ((El-Kharbotly, et al., 2003).

Table 2.3. Soil salinity classes according to Richards, (1954). ECe: Electrical Conductivity of a paste saturation extract.

Salinity class	ECe (dS m^{-1})	Salinity effects on crops
Non-saline	< 2	Salinity effects are negligible
Slightly saline	2–4	Yields of very sensitive crops may be restricted
Moderately saline	4–8	Yields of many crops restricted
Very saline	8–16	Only tolerant crops yield satisfactory
Extremely saline	>16	Only a few very tolerant crops yield satisfactorily

There are numerous options for sustainable management of salt-affected soils (Table 2.4) that can be combined with a vast potential of improved salt-tolerant species and cultivars, such as extending the choice of crops that can grow at each soil salinity level and increasing soil organic matter to improve soil structure (Eynard, et al., 2005).

Table 2.4. Management practices for agricultural use of salt-affected soils.

Type	Management practices
Hydraulic	Irrigation (leaching, method efficiency) Drainage (disposal, method efficiency) Mulching
Mechanical	Embankments, dikes, land shaping (leveling, ridging) Tillage (deep, chiseling, plowing, seedbed preparation, cultivation, no-tillage)
Amendment	Gypsum, lime, sulfur, animal & green manure, crop residues
Cropping system	Salt-tolerance (species, cultivars) Cycle (duration, timing, seed rates, transplanting) System (perennial & deep rooted crops, afforestation, continuous cropping)

2.2.2. Soil Fertility

Soil fertility refers to the ability of the soil to supply essential plant nutrients for plant growth and reproduction in the absence of toxic substances which may inhibit plant growth (www.fao.org). According to Sanchez, et al. (1997), soil fertility depletion in smallholder farms is the fundamental biophysical cause for declining per-capita food production in sub-Saharan Africa (SSA), where an average of 660 kg N (nitrogen) ha^{-1} , 75 kg P (phosphorus) ha^{-1} , and 450 kg K (potassium) ha^{-1} has been lost during the last 30 years from about 200 million ha of cultivated land in 37 African countries. In addition, soils in a large part of SSA are strongly weathered and inherently low in organic matter, and natural replenishment of nutrients during fallow periods is now insufficient to maintain soil productivity over the long-term due to increasing production demands (FAO and ITPS, 2015). Low fertility is exacerbated by soil moisture stress that constrains productivity on 85% of soils in Africa (Eswaran, et al., 1997).

Low nutrient status of most soils in SSA is further exacerbated by insufficient use of fertilizers and manure and by the practice of mono-cropping. Overall use of inorganic fertilizers in SSA is only 12 kg ha^{-1}, the lowest in the World, and soil nutrient depletion is widespread in croplands. Approximately 25% of soils in Africa are acidic and, therefore, deficient in P, calcium (Ca) and magnesium (Mg) and commonly contain toxic levels of aluminum (Al) (McCann, 2005). Use of fertilizer in the region typically involves application of less than 9 kg N ha^{-1} and 6 kg P ha^{-1} compared with typical crop requirements of 60 kg N ha^{-1} and 30 kg P ha^{-1}. Recent research estimates that, on average, every country in SSA has a negative soil nutrient balance and the amount of N, P and K added as inputs was significantly less than the amount removed as harvest or lost by erosion and leaching in all countries studied (Swift and Shepherd, 2007).

Although many farmers have developed soil management strategies to cope with the poor quality of their soil, low input of nutrients, including organic matter, contribute to poor crop growth and to the depletion of soil nutrients. Stoorvogel, et al. (1993) calculated nutrient balances for arable soils in 38 sub-Saharan countries for 35 crops for 1982-1983 and made forecasts for 2000. Subtracting values of the output (comprised of harvest, removal of residues, leaching, denitrification and erosion) from the values of the input (comprised of fertilizers, manures, rain, dust, biological N-fixation and sedimentation), the study reported average nutrient losses for SSA as follows: 22 kg N ha^{-1}, 2.5 kg P ha^{-1} and 15 kg K ha^{-1} for 1982-1983 along with a projected 26 kg N ha^{-1}, 3 kg P ha^{-1} and 19 kg K ha^{-1} for 2000. This indicated persistent nutrient mining over time (Bationo et al., 2012). FAO and ITPS 2015 estimate that 4 million Mg of nutrients are harvested annually in SSA, but <0.25 million Mg are returned to the soil in the form of fertilizers. For at least partial mitigation of these losses, certain management practices can improve soil organic matter and, therefore, soil fertility. Increasing soil organic matter content requires a sustained effort that includes returning organic materials to soils (crop and animal residues), efficient use of fertilizers and rotations with high-residue crops and deep- or dense-rooting crops. Other beneficial practices to soil are use of compost, cover crops or green manure crops, crop rotation, perennial forage crops, zero or reduced tillage and agroforestry (Bot and Benites, 2005).

2.2.3. Soil Acidity

Natural processes occurring in ecosystems can lead to the acidification of soils. Soil acidification normally occurs slowly in agricultural areas while ecosystem and soil development take place over long geological periods. In some areas, the quantities of acid released and deposited have been large enough to cause serious perturbations in the environment. Many soils worldwide are sufficiently acid to restrict the growth and/or performance of roots of sensitive crops (Ulrich and Sumner, 2012). These authors have pointed out that soil acidity is one of the major factors regulating the species composition of ecosystems and that limits crop production. They also reported the predominant conditions in acid soils to be: (i) low concentration of Ca^{2+}; (ii) high concentration of H^{+}; (ii) high ammonium/nitrate-ratio; (iv) high concentration of Al^{3+}; and (v) high concentrations of Fe and Mn ions and compounds.

According to FAO and ITPS (2015), acidification of agricultural soils is primarily associated with the net removal of base cations and the direct addition of acidifying inputs (e.g. ammonium-based N fertilizer or long-term organic matter turnover reactions) to inherently low-pH soils, which have a low capacity to buffer added acidity. It is most prevalent on ancient, highly weathered soils.

Soils in our area of study are saline acid sulfate soils (Sadio and Van Mensvoort, 1993) and the key point for understanding the pedogenesis is the mangrove vegetation that colonized the alluvium in the floodplain of the last transgression (Furian, et al., 2011). The latter authors reported that in the vicinity of mangrove roots, sulfur-reducing bacteria accumulated potential acidity as pyrite derived from inputs of seawater S at each flood tide. After the dissolution of alkalinity by the biological reduction and its removal from the system, the equivalent amount of potential acidity precipitates around the roots as solid pyrite. Pyrite contents are usually between 1 and 2%. In fact, acid sulfate soil formation was encouraged by oxidation in the soil profile during the last marine regression. Pyrite (FeS^2) oxidation proceeds in several stages which are common in most acid sulfate soils: (i) slow formation of ferrous iron (Fe^{2+}), sulfate (SO_4^{2-}) and protons (H^+) at a pH close to 7; (ii) when pH drops to below 4, pyrite oxidation increases and the bacterium *Thiobacillus ferroxidans* catalyzes ferrous iron oxidation to ferric iron (Fe^{3+}); (iii) the ferric ion acts as a pyrite oxidant and generates more ferrous iron; (iv) the overall oxidation of one molecule of pyrite yields four protons. The acidity in turn reacts with other soil minerals, releasing major constituents such as K, Mg, Al, Fe and silicon (Si) into soil solution.

Jarosite, stable in very acid conditions, is a very common intermediary K and Fe sulfate mineral, forming bright yellow mottles in acid sulfate soil profiles. Jarosite is ultimately hydrolyzed to iron oxides, predominantly goethite and sometimes hematite. In the Peanut Basin of Senegal, acid sulfate soils with jarosite occur in low terraces liable to periodically flooding and are affected by salinity at levels depending on tides and water table (Sadio, 1991).

Neutralizing the actual acidity of acid sulfate soils is the main soil management objective. To this end, lime can be used, and it is effective. However, lime requirements for acid sulfate soils can be very high since every 1% pyritic-S will require approximatively 60 Mg ha-1 to neutralize just the upper 15 cm. Liming is an effective response to control acidity of surface horizons, but rates of lime addition lag behind required levels even in developed countries like Australia and continuing loss of yield occurs (FAO and ITPS, 2015). However, in some areas where lime is not available or affordable because of low incomes, the potential use of organic matter to mitigate both acidity and salinity should be investigated.

Organic amendments

Using organic amendments in saline acid sulfate soils can provide many benefits. By releasing nutrients slowly through the decomposition process, they constitute an important source of nutrients. Soil physical, chemical and biological properties can be improved by organic amendments. Bulk density, soil porosity, aggregation, and water holding capacity are positively affected by organic matter. These conditions can favor salt removal from the root zone. Organic matter is also a source or C and N for microorganism activities (decomposition and reproduction). Soil chemical properties like pH and cation exchangeable capacity can be increased, which can balance the acidity of the soil. Indeed, organic matter binds and chelates toxic Al, Fe and other metals, and drastically slows down the rate of further pyrite oxidation since that is driven by Fe^{3+}. Another advantage of this approach is that organic matter is readily available and inexpensive.

2.3. Pearl millet

2.3.1. Origin and Domestication

Cereals are important world crops in terms of production, land cultivated, and nutritional composition. Cereals occupy a prominent place and contribute heavily to the human diet as an important source of starch. In Africa, the domestication of cereals has led to the emergence of important cereal crops like pearl millet (*Pennisetum glaucum* [L.] R. Br.) in Sahelian Africa

(Oumar et al., 2008). Pearl millet, also classified as *P. americanum* (L.) Leeke or *P. typhoides* (Burm.) Stapf and C.E. Hubb, is an important cereal of traditional farming systems in tropical and subtropical Asia and sub-Saharan Africa (Jana Kholová, 2010).

Pearl millet is a major crop of the sub-Sahelian area from Senegal to Sudan (Figure 2.1). The greatest morphological diversity in pearl millet is observed in western Africa, south of the Sahara Desert, and north of the forest zone. The wild progenitor occurs in the drier northern portion of this zone (black triangles in Fig. 2.1). It is believed that pearl millet was domesticated some 4000 years ago at its place of origin and from there it reached eastern Africa, before spreading to India ~3000 years ago and to southern Africa ~ 2000 years ago (Oumar et al., 2008). India is considered as the secondary center of diversity (Brunken et. al., 1977).

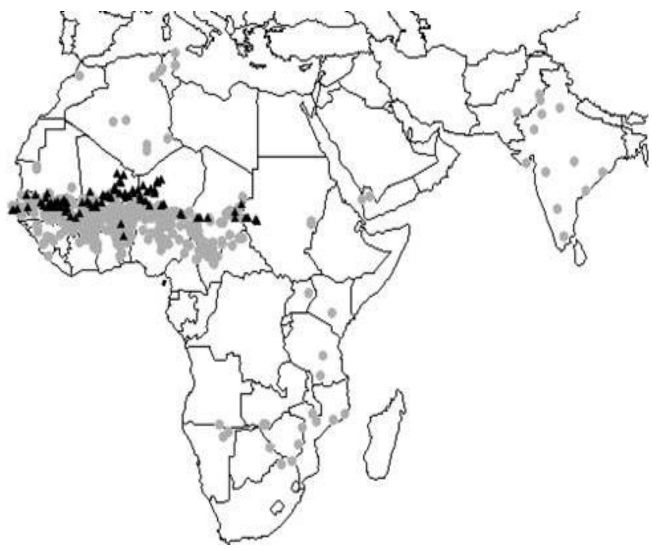

Figure 2.1. Geographic distribution of the pearl millet accessions. Source: Oumar et al., 2008.

The sample included 355 cultivated (gray dots) and 84 wild accessions (black triangles) collected from North Africa (Algeria, Morocco, and Tunisia), West Africa (Benin, Burkina Faso, Ghana, Guinea, Mali, Mauritania, Niger, Nigeria, Togo, Sierra Leone, and Senegal), Central Africa (Cameroon, Chad, Sudan, and RCA), East Africa (Malawi, Zimbabwe, Zambia, Tanzania, Kenya, and Namibia) and Asia (India, Pakistan, and Yemen)

The primary gene pool of pearl millet, defined as all crop plants, both cultivated and spontaneous, with which the crop freely hybridizes to produce fully fertile offsprings was reported by Brunken (1977) and is divided into three morphologically distinct units (Figure 2.2):

Wild plants which exhibit no cultivation characteristics and are not dependent upon man for their survival;

Weedy plants having intermediate morphology which occur exclusively in association with pearl millet cultivation and are indirectly dependent upon man;

Cultivated pearl millets whose survival is directly linked to man's agricultural activities.

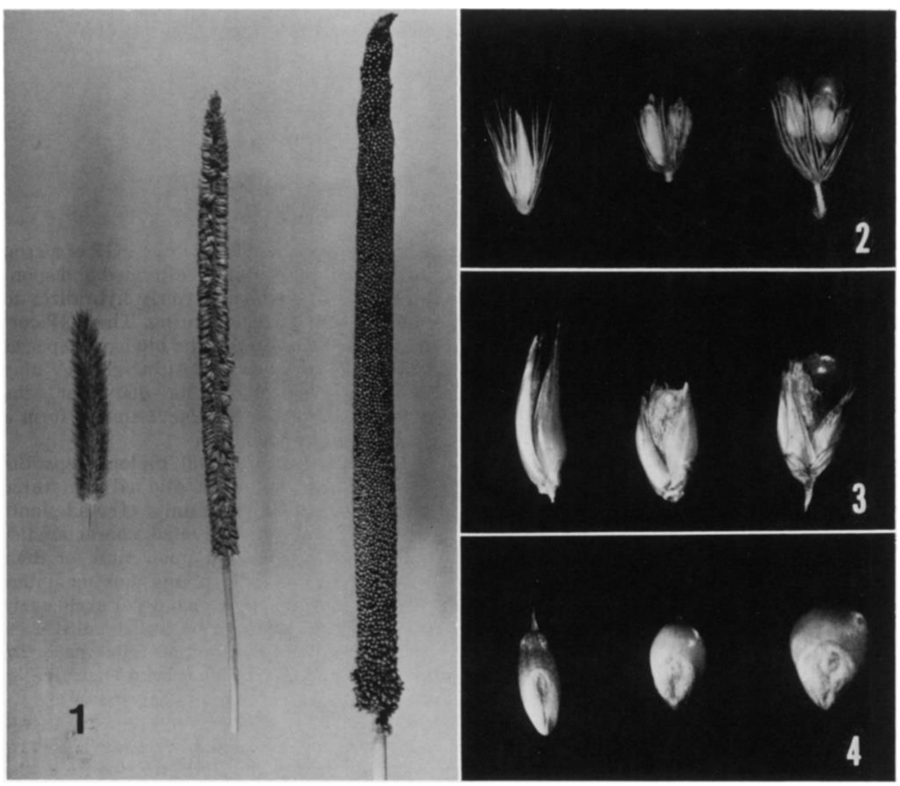

Figure 2.2. Examples of the three morphological variants included in the primary gene pool of pearl millet. Left: The wild progenitor. Middle: The intermediate, weedy type. Right: Cultivated pearl millet. **1.** Inflorescences. x 1/3. **2.** Involucres. x 2 1/2. **3.** Spikelets. x 6. **4.** Caryopses. x 7. Source : Oumar et al., 2008.

2.3.2. Importance of Pearl millet

Pearl millet is grown on over 31 million ha worldwide, with a production of 27.8 million Mg (FAO, 2016). Millions of poor rural families, mostly in the drought-prone areas where rainfed agriculture is commonly practiced, depend on this crop (Jana Kholová, 2010). Ranked sixth after rice, wheat, maize, barley and sorghum in terms of area planted, pearl millet (Figure 2.3 A & B) is one of the most extensively cultivated cereals in the world.

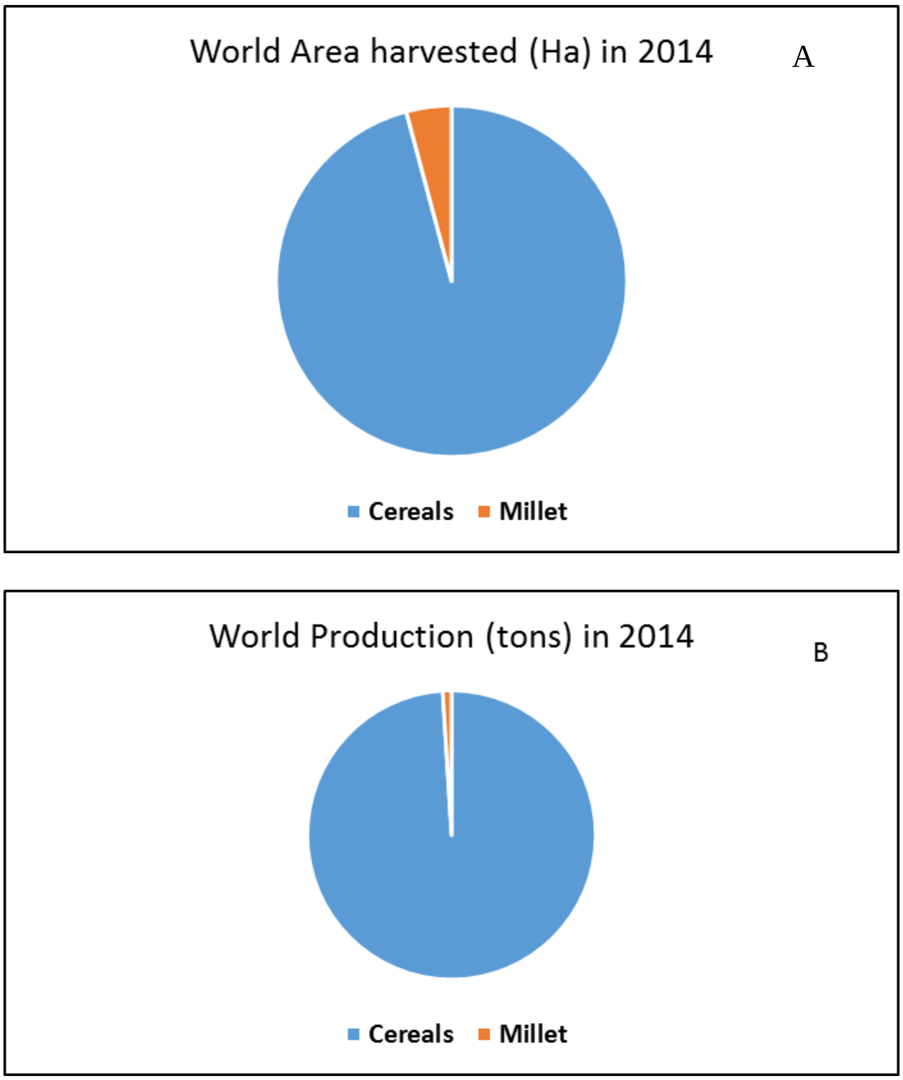

Figure 2.3. World cereals and millet harvested areas (A) and production (B) in 2014. Data from FAOSTAT 2016.

The crop is widely cultivated in drought-prone semi-arid regions of Africa and the Indian subcontinent, mostly for food. In some parts of the world (USA, Australia, Southern Africa, and South America), pearl millet is grown as a forage crop. Other uses of pearl millet include a potential source of biofuel (Wu, et al., 2006), as animal fodder, building material and fuel for cooking. As a result, millet crop residues are not used as soil organic matter source in some areas like in the "Peanut Basin," the main area where pearl millet is largely grown in Senegal (Figure 2.4).

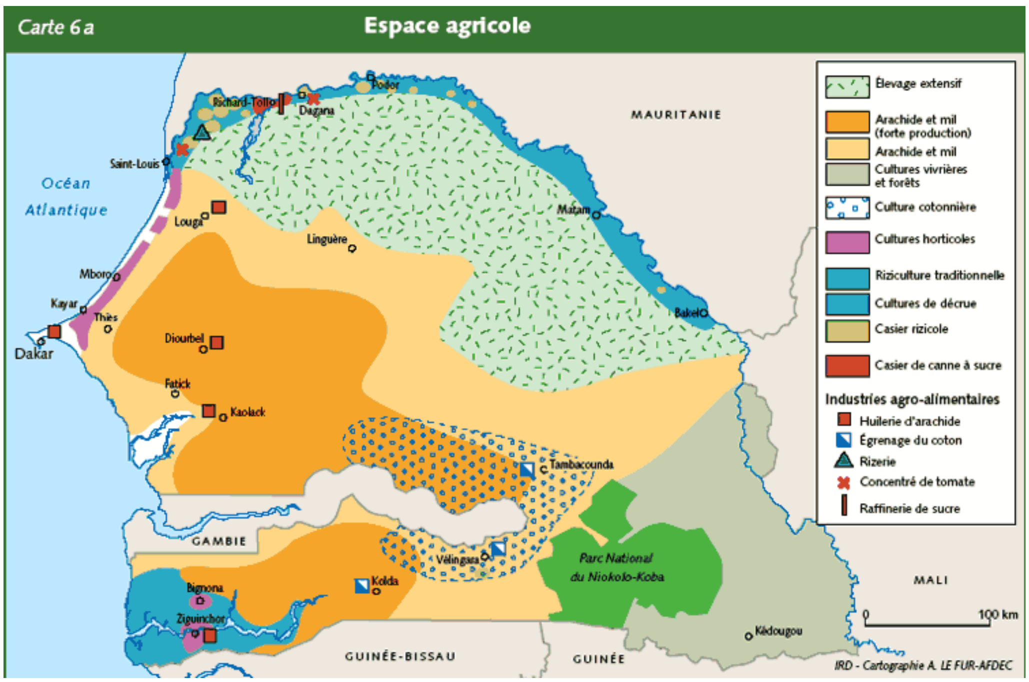

Figure 2.4. The major areas of cereal cropping in Senegal. Source: IRD http://www.cartographie.ird.fr/SenegalFIG/senegal_pdf/Espace_agricole.pdf

In Senegal, pearl millet is first in cultivated land areas and grain production. Its production has increased since the independence of the country (1960), although the seed production remained constant (Fig. 2.5).

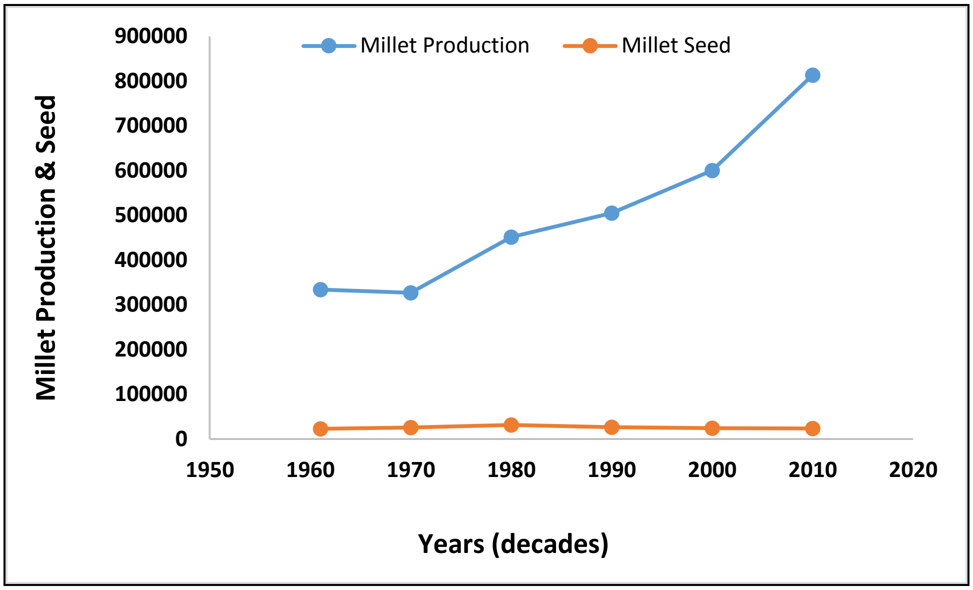

Figure 2.5. Pearl millet production and seed (tons) in Senegal from 1960 to 2010 (FAO, 2016)

Pearl millet is also important because of its ability to grow in severe environments. The crop has wide adaptability and is especially valuable in very hot and dry areas and on soils too poor for maize and sorghum (Khairwal, et al., 2007). These authors reported that pearl millet is more efficient in utilization of moisture and has a higher level of heat tolerance than sorghum and maize. This can be explained by two mechanisms. First, pearl millet stomata play an important role in minimizing crop water use in pre-anthesis water deficit (Winkel, et al., 2001). Second, pearl millet's water-saving mechanism operates under non-stressed conditions, leaving more water available in the soil profile for grain filling which can be beneficial for terminal stress conditions (Kholová, et al., 2010).

Over 93% of pearl millet grain is used as food, and the remainder is divided between animal and poultry feed (7%) (Khairwal, et al., 2007). As a principal source of energy, protein, vitamins and minerals for millions of poorest people in Africa and Asia, pearl millet generally has 9 to 13% protein with a large variation among genotypes ranging from 6 to 21%. Its use as a food crop is limited to the developing countries where the cropping system may differ from location to location.

2.3.3. Cropping Systems

The Peanut Basin of Senegal is the principal millet production region in the semi-arid areas of central Senegal. In this part of the country, there are two cropping systems for pearl millet (monocropping and intercropping). Indeed, millet is cultivated either as sole crop or in association with crops such as cowpea, sorghum and peanut (Diangar, et al., 2004). Local farming systems include a mix of compound and bush fields cultivated by rural households. The former fields that surround homesteads and are permanently cultivated, but receive various amount of amendments while bush fields are located at some distance from homesteads (Roudier, et al., 2014). Because of that, they receive less input than the compound fields. According to these authors, farmers usually plant millet prior to the rain, applying varying amounts or organic manure, and sometimes, chemical fertilizers. In this system, pearl millet is cultivated in lighter soils (Entisols known locally as joor), maize in heavier ones (Alfisols known locally as deg), while peanut is preferentially cropped in intermediate soils. In this area, Entisols have high iron content and low organic matter whereas the Alfisols are more weathered and have higher clay, silt and organic matter content. Two millet cultivars have routinely been grown: the *pod* or early millet (90 days) cropped in the compound fields and reserved as food for exceptional events such as farming works, religious ceremonies, etc., and the *matye* or late millet (120 days) in the bush fields where it was intercropped with sorghum and peanut (Lombard, 1993). Nowadays, the former is predominant and coexists with new improved millet cultivars.

In Sub-Saharan Africa, pearl millet is increasingly being intercropped with shrubs (Lahmar, et al., 2012). Such native perennial woody shrubs provide both nutrient and moisture-related benefits to pearl millet in the Senegalese Peanut Basin (Dossa, et al., 2009).

2.3.4. Plant growth

Pearl millet seeds germinate in 2 to 3 days at optimum temperatures (25 to 30°C) and moisture. When these conditions are met, the seeds swell due to moisture absorption (Khairwal, et al., 2007). Then, the seed coat breaks and a small shoot (coleoptile) and a primary root (radicle) develop. Initially, the young seedlings take nutrients from the endosperm of the seed. Millet has many stages of growth and typically needs about 90 and 100 days between the emergence and the maturity of the grains. Figure 2.6 shows the main growth phases of pearl millet.

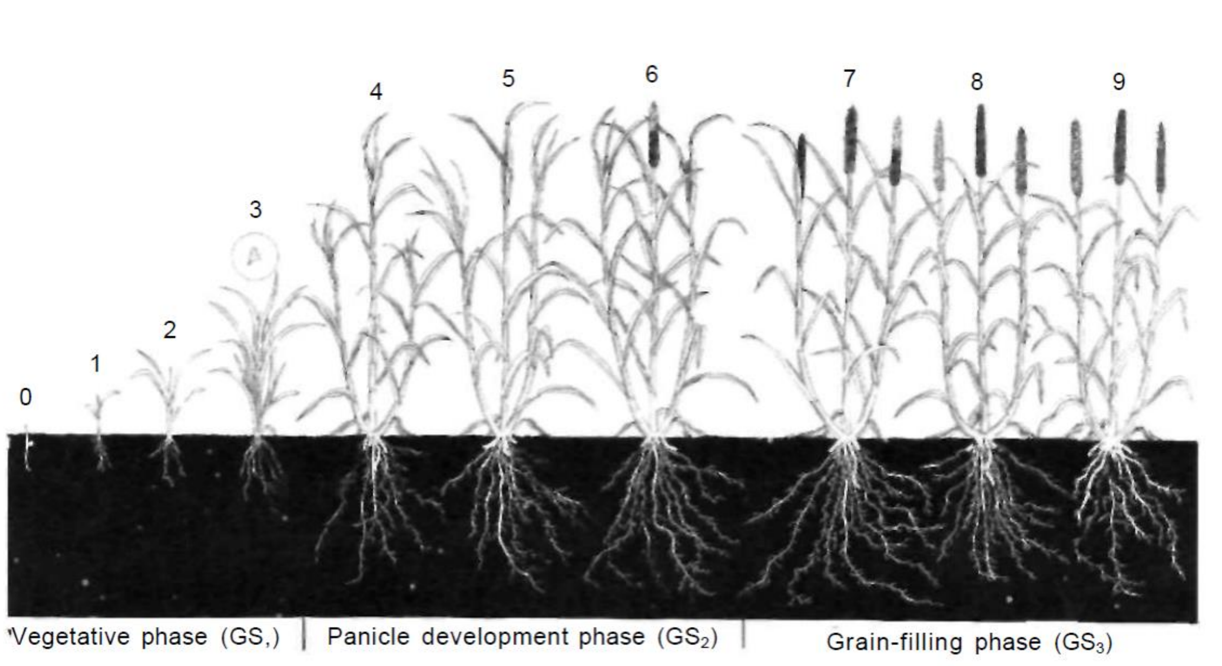

Figure 2.6. Schematic diagram of the major growth phases of pearl millet (GS1, GS2 and GS3). The number 0 to 9 illustrate the detailed stages of growth of pearl millet (Maiti and Bidinger, 1981). Stages: 0 (coleoptile visible at soil surface), 1 (third leaf visible), 2 (fifth leaf visible), 3 (panicle initiation), 4 (final of flag leaf visible), 5 (panicle extended in flag leaf sheath), 6 (stigma emergence), 7 (milk stage), 8 (dough stage) and 9 (black layer formation). Pearl millet

life cycle can vary from 60 days (early cultivars) to 180 days (late cultivars) (Bezancon, et al., 1997)

2.3.5. Yield and Varietal Selection

In Senegal pearl millet yield varies from 0.5 to 3.5 Mg ha^{-1} depending on cultivar, management and environment. This range of yield is far lower than what is reported by (Mullins and Reeves, 1995) whose study revealed that pearl millet grain yields can exceed 5.7 Mg ha^{-1} in slightly acidic soil condition with high residual P in southern Alabama. Similarly grain and biomass yield of 5.3 and 16.7 Mg ha^{-1}, respectively have been reported in Nebraska (Maman, et al., 2003). According to FAOSTAT (2016), pearl millet yield has increased from the 60's, but it is still under 1 Mg ha^{-1} (Fig. 2.7).

Several studies have been conducted to develop new pearl millet cultivars and hybrids for high grain yield. Agronomic variations among pearl millet genotypes have been reported earlier by Khairwal et al. (2007). These authors study may serve as a guide for breeding and selection depending on the purpose for which pearl millet is being grown, such as for forage (Sedivec and Schatz, 1991)or as a grain (Dewey, et al., 2009).

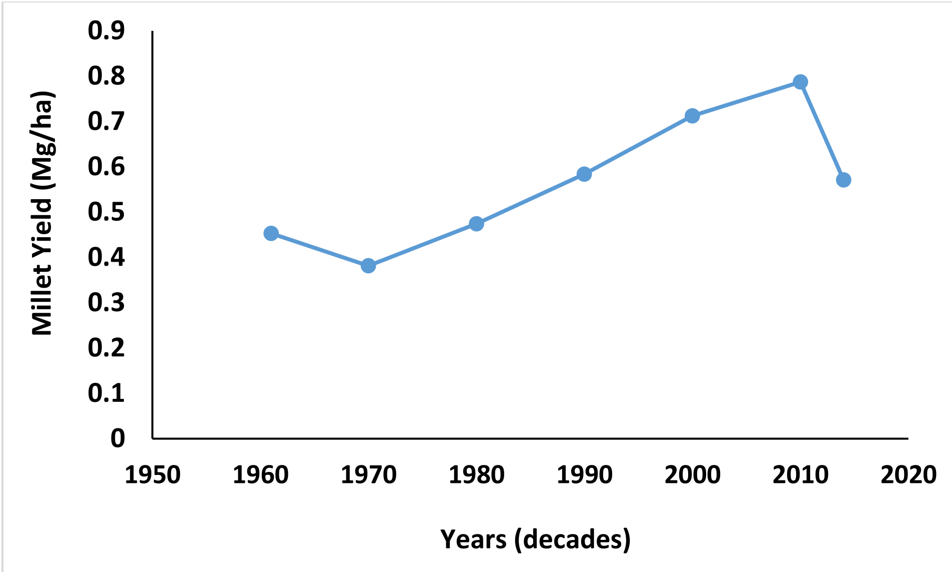

Figure 2.7. Evolution of millet yield in Senegal from 1960 to 2010 (FAOSTAT, 2016)

2.3.6. Drought and Salinity Tolerance

Originally a wild plant in Africa, pearl millet is a grass whose evolution under the pressures of drought and high temperatures explains its ability to tolerate drought, soil toxicities and extremes of temperature more effectively than other cereals like wheat and rice (Khairwal, et al., 2007). Faced with scarcity of water resources, drought is the single most critical threat to world food security (Farooq, et al., 2009). Because the world's water supply is limited, future food demand for rapidly increasing population pressures is likely to further aggravate the effects of drought (Somerville and Briscoe, 2001). According to Earl and Davis (2003), the reduced canopy absorption of photosynthetically active radiation, decreased radiation-use efficiency and reduced harvest index are the three main mechanisms that reduce crop yields due to soil water deficits. Plant water deficit can also result from salinity and corresponding effects on root water uptake. Many species of higher plants, including most crops, are subjected to growth inhibition under high salinity conditions (Hussain, et al., 2015). The salt-induced inhibition of plant growth is caused both by osmotic effects on water uptake and by variable effects on plant cell metabolism. While the first component can bring about water deficit, the excess of a specific ion (e.g. Na) can cause toxicity and can induce nutritional disorders (Khatoon, et al., 2010).

Millet cultivars

Characteristics of seven cultivars used in this study are reported in Table 2.5. The number of days between sowing and harvest varies from 75 to 120. SOSAT C88 has the smallest plant height (180 cm), and ICMV IS 88102 the greatest. Tillers number ranges from 3 to 7, and tiller length from 25 to 55.

Table 2.5. Some morphological traits and life cycle of seven pearl millet cultivars used in this study (*http://mita.coraf.org*). These values are means.

Cultivars	From sowing to harvest (days)	Height (cm)	Total tillers (no.)	Panicle length (cm)	Grain Yield (Mg ha^{-1})
GAWANE	85	250	5-7	55	2.5
IBMV 8402	75-85	224	4-6	51	2.5
ICMV IS 88102	120	270	3-4	38	1.4
IKMP1	115-120	260	5-8	30	1.7
IKMP2	105	250	3-4	40	1.6
IKMV 8201	90	200	3-4	27	1.0
SOSAT C88	90	180	-	25-30	1.3

In view of the previously described literature, the objectives of the present study were (i) to compare responses of three millet cultivars to salinity and two local organic amendments in a field study; (ii) to assess the salt stress effect on germination and early seedling growth of seven cultivars of pearl millet under saline conditions, and (iii) to evaluate the effects of different amendments on the germination and vegetative stage of SOSAT C88, a pearl millet cultivar, under saline conditions.

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3. Chapter 3: Effects of amendments on pearl millet (*Pennisetum glaucum*) cultivars grown in acid, saline soil: Field, Laboratory and Greenhouse studies

3.1. Abstract

In West and Central of Senegal, increasing soil salinity has become one of the main limiting major factors limiting agricultural production. Crop production on saline soils can be substantially improved by the use of local and available organic amendments and millet genotypes tolerant to salt. We investigated the salt tolerance of millet cultivars and the effects of amendments on millet growth in a two-year field study and in a man-made saline acid sulfate soil in a greenhouse study. In the greenhouse experiment cultivars SOSAT C88, IBMV 8402, GAWANE, IKMP1, IKMP2, IKMV 8201 and ICMV-IS 82102 were grown in four levels of salinity, expressed in electrical conductivity, EC (0.3, 2.1, 4.2, 5.2, and 6.3 dS m^{-1}). Soil amendments (compost from Senegal, CS; peanut shells from Senegal, PSS; cowpie dairy manure compost, CDMC; Prince William County yard waste compost, PWC; inorganic N, P and K fertilizer, NPK; and phosphogypsum, PG) were compared for their effects on soil and the plant responses of the most tolerant cultivar. Cultivars SOSAT C88 and IBMV 8402 performed best in saline greenhouse media, and the fertilizers that elicited the best millet plant responses in the greenhouse experiment were PWC, PSS66 and NPK. Phosphogypsum exacerbated the salinity effect by increasing growth media electrical conductivity. In the field, peanut shell allowed the best plant performance while rainfall was more important on EC than treatments. Our results suggested that cultivars IBMV 8402 and SOSAT C88 be cultivated in saline soils amended with peanut shells.

3.2. Introduction

Major soil limitations for agricultural productivity in Senegal include infertility, low organic matter-content, high acidity, and salinity (Diome and Tine, 2015, McClintock and Diop, 2005). Until 1971, soil acidification in Sine Saloum area, where Ndoff is located, was not widespread. According to (Marius, 1976) and (Sadio, 1989), the catastrophic drought of the seventies was the main cause of soil acidification in this part of the Peanut Basin. The rainfall deficit and the resulting falling water-tables have led to pyrite oxidation and formation of acid sulfate soils.

Drought has also exacerbated soil salinization. The effects of salinity occur in approximatively 34% of the soils, which comprise 2.5 million ha or two thirds of arable lands in Senegal (Mondiale, 2012). Soil salinization is a global ecosystem concern that is likely to increase with future climate change (Shahid, 2013). Excessive amounts of soluble salt have adverse effects on soil properties and limit crop production (Liang, et al., 2005). When plants are grown under saline conditions, their tissues accumulate Na^+ and Cl^-, which results in inhibiting mineral nutrient uptake, especially $Ca^{2+,}$ K^+, N and P (Kaya, et al., 2001). Plant growth is also further inhibited by the resulting high osmotic potential of the external medium and the adverse effects on gas exchange, photosynthesis and protein synthesis (Romero-Aranda, et al., 2001).

Organic amendments including composts have the ability to improve soil physical, chemical and biological properties of degraded lands. More specifically, they have been used to remediate salt-affected soils by improving their physical, chemical and biological properties (Liang, et al., 2005, Walker and Bernal, 2008) while promoting improved plant growth. By improving soil structure, porosity and density, organic amendments can increase both water infiltration and water holding capacity (Council, 2001).

Another major benefit of organic amendments is increasing soil organic matter. Many soils in West Africa are highly weathered with low to moderate fertility (Schlecht, et al., 2007). In this area, sandy soils are characterized by low organic matter content, low native P concentration and little cation exchangeable capacity (CEC) (Manu, et al., 1991). (Ganry, et al., 1978) reported that organic matter (straw incorporation) was important in increasing the efficiency of nitrogen fertilizer on pearl millet. Because composts are made from different feedstocks, they will differ in their physiochemical properties. As a result, when used for salt-affected soil reclamation, they might modify soil properties differently (Lakhdar, et al., 2009) and improve plant growth differentially.

In Senegal, classical sources of organic matter (crop residues and manures) are also used for feeding animals and construction, respectively. Based on their availability, two organic amendments can be used for saline acid sulfate soils. These considerable sources are peanut shells and filao compost. Senegal is ranked 7th in peanut production worldwide (Noba, et al., 2014) and each year a large amount of peanut shells is produced, rending this product usable for agricultural purpose. Rich in lignin, peanut shells composted in mixture with peanut stems or chicken droppings had C:N ratios of 36 and 23, and a CEC of 44 and 47 cmolc kg^{-1}, respectively (Mallouhi, et al., 1993). On the other hand, filao tree plantations in the Niayes region between Dakar and Saint-Louis in Senegal produces large quantities of litter used as biofertilizer by local farmers. According to (Mailly and Margolis, 1992) leaf litter has been estimated at 3.3 Mg ha^{-1} in 6 to 34-year-old plantations. Diagne, et al. (2013) mentioned its extensive use as compost to improve soil fertility. Its litter compost also improved plant growth and yield (Soumare, et al., 2004).

Soil chemical amendments like phosphogypsum can also be used for salt-affected soil reclamation. A byproduct of the phosphate fertilizer industry, phosphogypsum results from the production of phosphoric acid from rock phosphate and subsequent neutralization reactions. Because of that, its composition depends on the type of rock. Its major constituents, Ca, P, Sulfur (S) and Fluorine (F) are found at concentrations of 1-240 g kg^{-1}. Additional elements found at concentrations <800 mg kg^{-1} include K, Mg, molybdenum (Mo), cadmium (Cd), and radioactive elements like radium (Ra) (Korcak, 1998). According to Sumner (1995), gypsum has been used in four major applications in agriculture: (i) its first use was on sodic soils as a corrective treatment to improve their very poor physical properties (soil structural decline resulting from clay dispersion which, in turn, causes blockages in pore continuity reducing the free movement of water in the soil profile). Gypsum application alleviates this adverse condition caused by Na ions; (ii) as a source of nutrients, gypsum has been proven to be an excellent source of Ca and S; (iii) with a rate between 5 and 10 Mg ha^{-1}, it has been shown to counteract the negative effects of subsoil acidity on plant root development allowing crop to harvest water from subsoils previously beyond their reach, and (iv) gypsum application at a rate lower than 5 Mg ha^{-1} reduces the formation of a crust or seal when the soil surface is exposed to the energy of impacting raindrops by promoting clay particle flocculation.

Both phosphogypsum and lime provide Ca which is needed in large quantities by crops (Sumner, 1995). Most of Ca is used as a cell wall constituent, while the remaining proportion plays a vital function in membrane and hormone functioning (Hanson, 1984). Bartholomew (1928) reported that typical Ca contents in plant tissue range from 0.1% in seeds to as high as 3-4% in the leaves of certain crops. Like most of the nutrients, Ca availability varies with pH. Generally, in soils with neutral pH, exchangeable and soluble Ca are sufficient to supply most of crop requirements. However, in acidic soils, there is a decrease of exchangeable Ca, and particularly, the soluble Ca sometimes replaced by high toxic levels of Al. In such conditions, calcitic (CaCO3) or dolomitic (CaCo3•MgCo3) limestone is the ameliorant of choice because both products supply Ca and precipitate labile Al, therefore alleviating its toxic effect. In view of the need to alleviate both salinity and acidity, it was necessary to include lime and phosphogypsum in the current research.

According to (Tejada, et al., 2009), the adverse effects of soil salinity on plants depend on tolerance of those plants to saline conditions. Therefore, effective strategies to improve food production include the identification of plant cultivars less sensitive to salinity and the use of locally available and affordable organic amendments capable of ameliorating the effects of salinity in agricultural lands.

The study objectives were to identify the effects of a range of salinity on various pearl millet cultivars (greenhouse study), and to compare the effects of various amendments applied to acid, saline soils on soil fertility parameters and crop responses (greenhouse and field studies).

3.3. Materials and Methods

3.3.1. Greenhouse Studies

Two greenhouse studies were designed to (1) quantify the effects of salinity on various pearl millet cultivars and (2) to compare the effects of various amendments on crop response to salinity and acidity.

Soil characterization

Two types of soil were used in the greenhouse studies. A soil designated Old Hickory (the locale in Dinwiddie County, Virginia from where the soil was collected) is an Ultisol from the Orangeburg series (fine-loamy, kaolinitic, thermic Typic Kandiudults). The soil sampling location has been managed in perennial forage cover for over a decade, but the immediately adjacent field is managed for peanuts, cotton, and corn-wheat-soybeans.

A second soil was fabricated from local Virginia mineral substrates to approximate the chemical and physical properties of a Senegalese coarse-textured, infertile, acid, saline soil. This soil was a mixture of a washed sand (85%), a saline dredge spoil material (Cheatham, 10%) and the Bojac series (5%), and is designated WSCB. The Cheatham is a dredge material from the Cheatham Naval Annex on the York River, Virginia, which barged to Shirley Plantation on the James River in Charles City Co. Virginia, and placed into an upland utilization area atop a previously reclaimed sand and gravel mine (Daniels, et al., 2007). The Bojac Series (Coarse-loamy, mixed, semi-active, thermic Typic Hapludults) is a deep, well-drained soil from Greenville County, Virginia.

Soil samples were air-dried and ground to pass through a 2-mm screen before the particle size analysis with pipette method (Gee, et al., 1986). The pH was determined with a ratio of 1:2

(soil: water), and the EC was measured in soil saturation extracts (U.S. Salinity Laboratory Staff, 1954). Routine analyses were performed on pre-plant and residual soil samples of greenhouse experiment 2 by the Virginia Tech Soil Testing Laboratory for P, K, Ca and Mg by the Mehlich I method and for pH by 1:1 method (Maguire and Heckendorn, 2011). Total C and N were analyzed by combustion with a Vario MAX CNS macro elemental analyzer (Elementar, Hanau, Germany).

Watering regime

Freely draining pots filled with the greenhouse growth media were used to calculate growth medium water holding capacity (WHC) for the purposes of watering regimes. Pots lined with coffee filters were filled with desired amounts of weighed air-dried soil (Weight #1) for each greenhouse experiment. The soil was thoroughly watered to ensure saturation, pots were covered with plastic wrap and secured with a rubber band to prevent evaporation, and undisturbed for 48 h to permit drainage of gravitationally-removed water. The plastic wrap was removed, and the remaining water, soil and pot were weighed. Subtracting the weight of the pot enabled calculation of media plus water held against gravitational forces to be calculated (Weight #2). The pots were replicated 4x. Equation 3 was used to calculate the amount of water in the soil at “soil WHC.”

$$\frac{\text{Weight 2} - \text{Weight 1}}{\text{Weight 1}} * 100 = \%\ \text{water in soil at soil WHC.} \qquad \textbf{Eq. 3}$$

The greenhouse container soils were watered during the plant production portions of the studies to maintain the moisture content at 85% WHC. Deionized water was used in both greenhouse experiments 1 and 2 due to its low EC (0.008 dS m^{-1}) and near neutral pH (7.13) because we did not wish to add additional salt or alter the soil pH.

Electrical conductivity calibration for soil salinity greenhouse study

Sodium chloride (NaCl) was used to establish salinity levels in the both Old Hickory and WSCB soils used to test the salt tolerance of various millet cultivars. Various rates of NaCl were used to develop a calibration curve with a range of electrical conductivities (EC). The soil was watered to 85% WHC. After an equilibrium period of 24 hours, the soil from each container was mixed and samples removed, air-dried, and analyzed for saturated paste EC as indicated by the US Salinity Laboratory USSL (1954). The concentrations of NaCl needed to achieve various EC values were provided by the calibration curve equations (Fig. 3.1; 3.2).

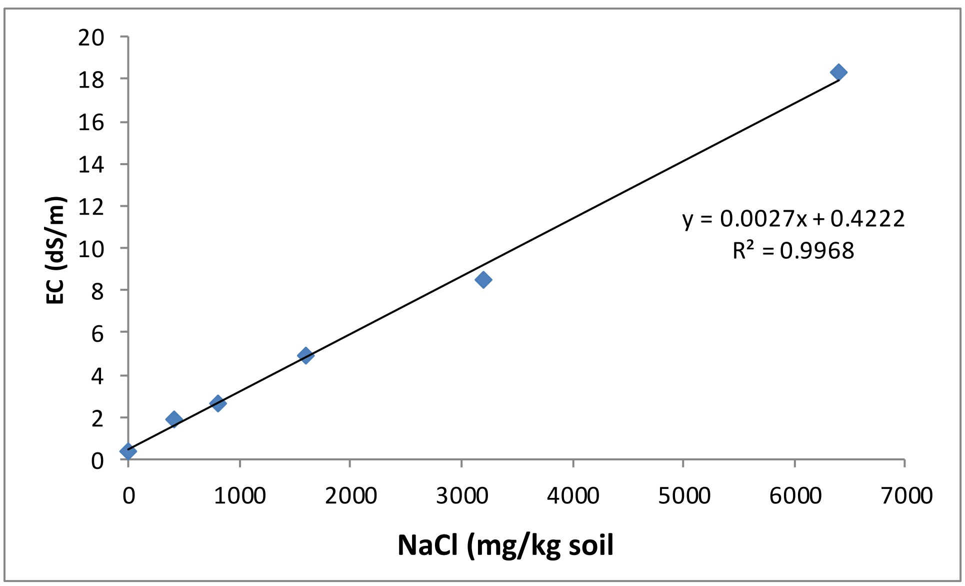

Figure 3.1. Electrical conductivity (EC) vs sodium chloride (NaCl) line whose equation was used to calculate the concentrations of NaCl to achieve desired EC for Old Hickory soil.

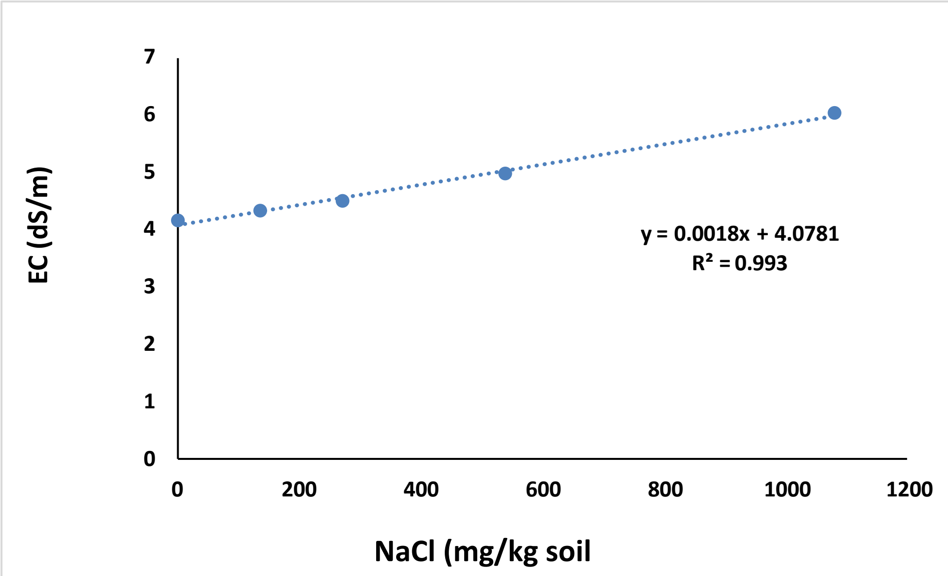

Figure 3.2. Electrical conductivity (EC) vs sodium chloride (NaCl) line whose equation was used to calculate the concentrations of NaCl to achieve desired EC for Washed Sand Cheathan Bojac.

Soil pH calibration

The greenhouse soils were limed to pH 6.2 (target pH for pearl millet) with calcium hydroxide ($Ca(OH)_2$) to ensure quick reaction. A calibration was performed for each soil to determine the rates of $Ca(OH)_2$ needed to achieve the target pH by amending 1 kg soil with increasing rates of the liming source. The soil was watered to 85% WHC and permitted to equilibrate during three days for Old Hickory soil and seven days for WSCB. Figures 3.3 and 3.4 show the calcium hydroxide vs pH calibration curves whose equation was used to calculate lime rates to achieve pH 6.2 for Old Hickory and WSCB, respectively.

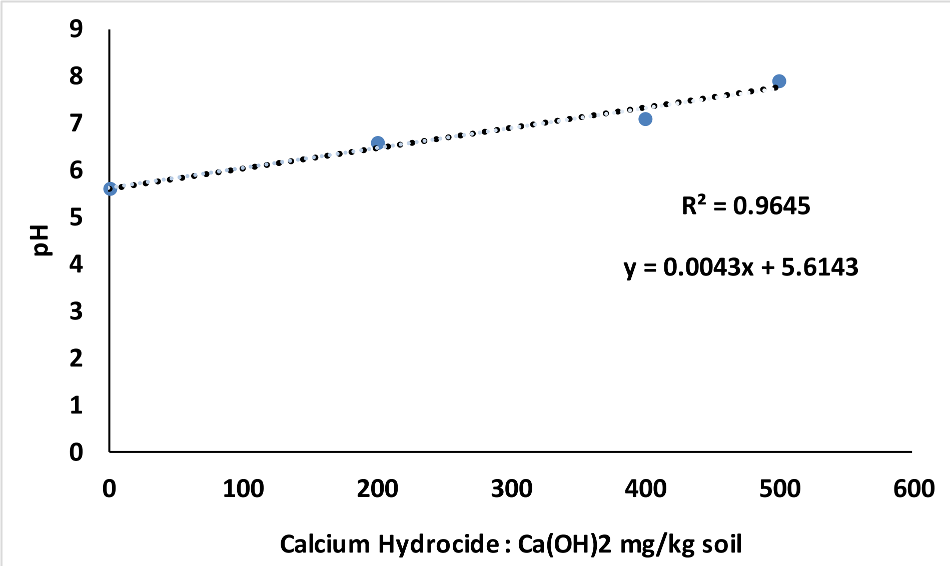

Figure 3.3. Calcium hydroxide vs pH line whose equation was used to calculate the required rate of lime for Old Hickory to attain pH 6.2.

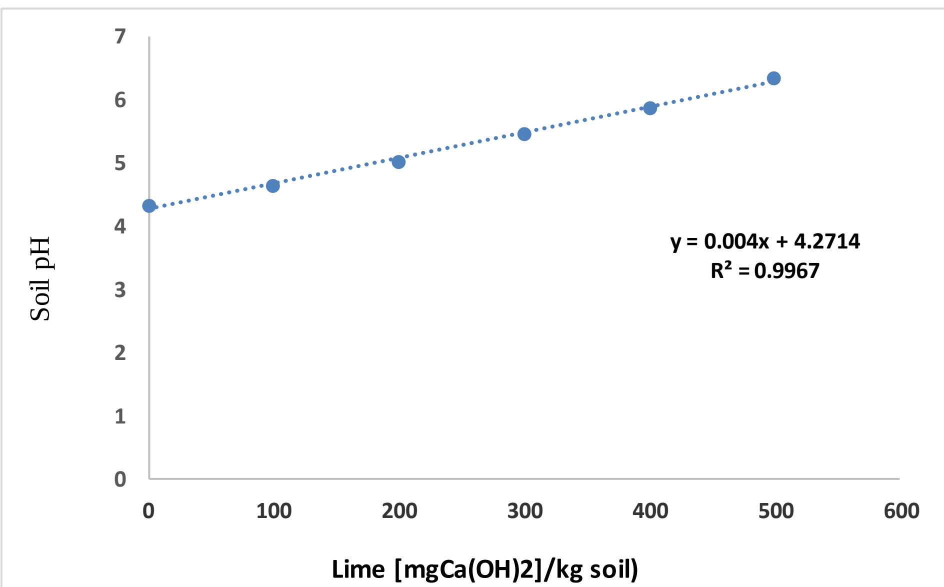

Figure 3.4. Calcium hydroxide vs pH line whose equation was used to calculate the required rate of lime for Washed sand Cheatham and Bojac soil to attain pH 6.2.

Greenhouse study 1: Experimental design

A completely randomized experimental design with 2 levels of liming (limed and unlimed), 5 NaCl concentrations, and 7 cultivars (IBMV 8402, IKMV 8201, ICMV-IS 88102, IKMP1, IKMP2, Gawane, and SOSAT C88) of pearl millet (Pennisetum glaucum (L.) R.Br.), each replicated 4x, was employed during summer 2015 to assess pearl millet cultivars tolerance to salinity. Each plastic pot (11.4 cm in diameter at the top and 9.4 cm in depth) was filled with 600 g air-dried Old Hickory soil. Soils were allowed to equilibrate for 24 hours after adding five rates of sodium chloride (0, 133, 300, 379 and 466 mg per 600 g of soil corresponding to 0.3, 2.1, 4.2, 5.2 and 6.3 dS m^{-1}, respectively) and watering to 85% WHC. The rates selected for this study were 0x (control; 0.3 dS m^{-1}), 0.5x (2.1 dS m^{-1}), 1x (4.2 dS m^{-1}), 1.25x (5.2 dS m^{-1}), and 1.5x (6.3 dS m^{-1}) the EC of the low salinity field soil (4.2 dS m^{-1}; El Hadji Faye, Personal communication). The pots were lined with plastic to prevent leaching.

Soil was sampled for chemical analysis prior to seeding by removing 115 g after complete mixing. The saturated paste EC of these subsamples was measured with an EC-meter (Model 2052, VWR International) in a CSES laboratory at Virginia Tech. Pots were weighted and watered twice with deionized water (DI water) to maintain soil at 85% WHC.

Five millet seeds were sown per pot. After planting the millet, pots were watered twice per day while the millet was germinating to ensure that the soil stayed moist. The experiment was conducted for 10 days, during which time emergence and early seedling vigor were compared among the seven cultivars to select the most tolerant to salinity for greenhouse study 2.

Greenhouse study 2: Experimental design

In December 2015, the washed sand Cheatham and Bojac mixture soil (WSCB) were processed similarly to Old Hickory soil described above, except for pot and plastic bag sizes, and the amount of soil per pot. One kg of air-dried WSCB soil was weighed into each 15.2-centimeter plastic pot (15.2 cm in diameter at the top and 14.7 cm in depth) lined with a plastic bag.

A factorially arranged, randomized completed block design consisting of 8 soil fertility amendments x 2 phosphogypsum rates x 4 replications was used. The eight soil fertility treatments were:

1. Control;

2. Compost from Senegal (CS5; applied at 5 g kg^{-1} of soil, which was the rate recommended and used in the field study in Ndoff, Senegal). This compost was locally and traditionally made from Filao tree (*Casuarina equisetifolia* L.) litter. NPK (15-15-15) was added to the treatment soil at 150 kg ha^{-1};

3. Peanut shell from Senegal (PSS5; applied at 5 g kg^{-1} plus NPK 15-15-15 at a rate of 150 kg ha^{-1} based on local agricultural recommendations);

4. NPK (40, 22, 47 mg kg^{-1}, respectively) calculated based on pearl millet requirement;

5. Compost from Senegal described above, but at a higher rate (CS48; applied at 48 g kg^{-1} of soil);

6. Peanut shell from Senegal described above, but at a higher rate (PSS66; applied at 66 g kg^{-1} of soil);

7. Cowpie Dairy Manure Compost (CDMC; applied at13 g kg^{-1} of soil);

8. Prince William County yard waste compost (PWC; applied at 44 g kg^{-1} of soil).

The four last treatment rates (nos. 5-8) were based on annual pearl millet N requirements and estimated plant available N (PAN) for each amendment based on laboratory analyses and commonly used N availability coefficients used in Virginia (DCR, 2014) for the compost products (Eq. 4). We based our application rates on the expectation that mineralization rates were 0.10 for Prince William County and Compost Senegal, 0.15 for Cowpie Dairy Compost, and 0.0 for Peanut shell.

PAN = (NO3-N) + (NH4-N x Vol) + (Organic N x Nmin) **Eq. 4**

Where Vol is the volatilization coefficient for NH3 and Nmin the mineralization coefficient for organic N.

Phosphogypsum (PG) was applied at 0 and 8.5 g kg^{-1}. The rate of 8.5 g kg^{-1} was based on an amount equivalent to 7.5 Mg PG per ha, which the mean of the recommended rate range (5 to 10 Mg ha^{-1}) (Sumner, 1995).

All treatments, including the control, received a basal treatment of 72 mg of NaCl and 483 mg of $Ca(OH)_2$ per kg of soil. These rates were calculated from the equations obtained from EC and pH calibration lines.

Organic amendment samples were analyzed by A&L Eastern Laboratories (www.al-labs-eastern.com) for total Kjeldahl N, NH_4-N, organic N and total solids total, phosphorous (P), total potassium (K), and pH (USEPA, 2009). The analyses were used to determine actual N, P and K applied. Total carbon (C) and nitrogen (N) were analyzed by combustion with a Vario MAX

CNS macro elemental analyzer (Elementar, Hanau, Germany) in Soil Fertility and Plant Nutrition Laboratory of Virginia Tech.

Based on its superior germination and emergence performance in experiment 1, cultivar Sosat C88 was used in the second experiment. Four replicates of 10 seeds were sown in each pot. Pots were water daily (morning and afternoon) with DI water. Ten days after sowing, seedlings were thinned to three per pot.

Sample collection/measurements and processing

Soil sampling

In addition to the methods described in soil characterization above, inorganic N was extracted from soils with 2 M potassium chloride (KCl) at a soil: KCl ratio of 1 g of soil to 10 mL of KCl. The soil-KCl mix was shaken mechanically for 30 minutes, and the resulting supernatant was filtered through 0.45-micron filter paper to give a filtrate free of suspended solids. The filtrate was then run through a Lachat 8500 Flow Injection Analyzer to determine NO_3-N by QuikChem Method 12-107-04-1-B (Knepel, 2003) and to determine NH_4-N by QuikChem Method 12-107-06-2-A (Hofer, 2001).

Plant measurements

Emerged seedlings were counted daily during the first week of the experiment and used to calculate the percentage emergence, which was calculated as the number of emerged seeds divided by the total of sown seeds multiplied by 100. Plant height from the soil surface to the top of the plant was measured 15, 30 and 45 days after sowing. The Normalized Difference Vegetation Index (NDVI) was measured using a GreenSeeker handheld sensor version 1.00 (Trimble Navigation Limited, 2012). NDVI is one of the most commonly used vegetation indices and has been directly employed as an indicator of vegetation vigor (Salinas-Zavala, et al., 2002). For each pot, the NDVI was measured from six points (3 from the top and 3 from the side of the plants) on each date. Values of this index range from 0.00 to 0.99. Absence of green leaves give a value close to 0.2 to 0.3 and a value close to +1 (0.8 - 0.9) indicates the highest possible density of green leaves. At the end of the experiment (45 days after sowing, DAS), plants were harvested, roots were washed and dried out with paper tissues before shoot and root fresh biomass were weighed, Plants were then oven-dried for 48 hours at 70°C before their dry biomass was measured.

Statistical analysis

The data were analyzed by analysis of variance (ANOVA). Tukey's HSD contrast was utilized to normalize and run multiple comparisons on soil and plant parameters. For experiment 2, only plant height was repeatedly measured, and analyzed so.

3.3.2. Field study

Site characteristics

Location

The study was performed in 2014 and 2015 in the village of Ndoff. Located in the central west of Senegal (Figure 3.5), Ndoff belongs to both of the region and the administrative division of Fatick, and is part of the Peanut Basin.

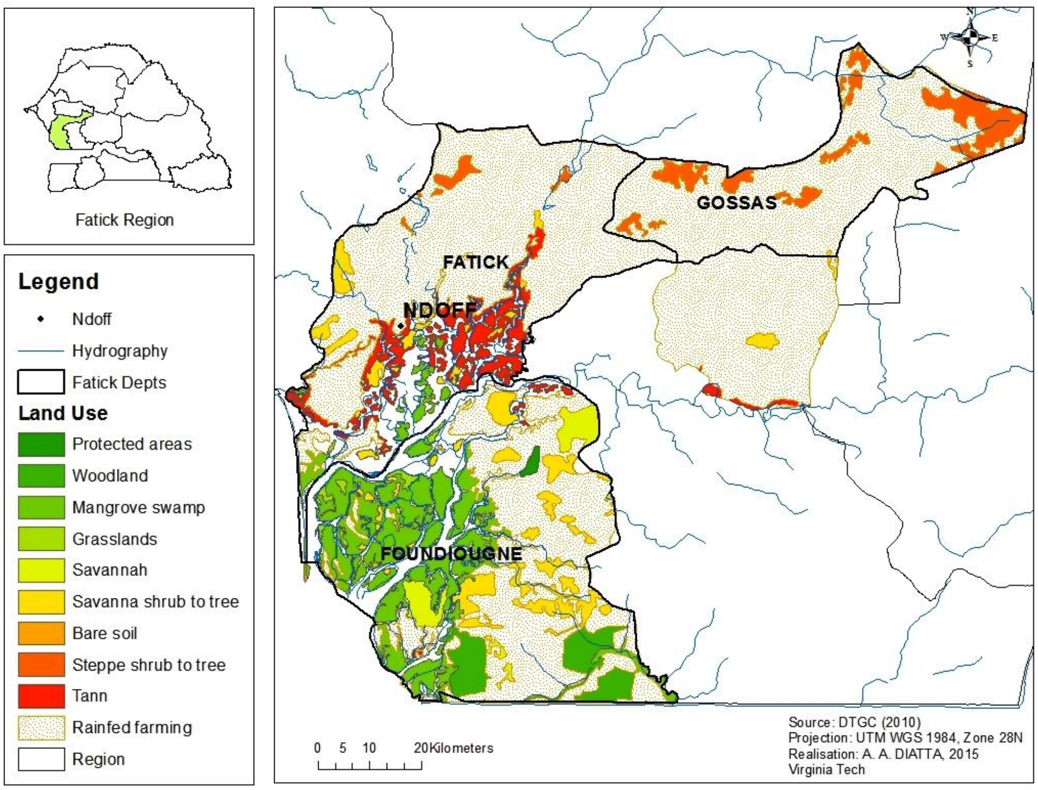

Figure 3.5. Location of the site of study (Ndoff) in the department of Fatick, Senegal.

Climate

Ndoff has a tropical Sudanian climate. To characterize its climate, rainfall data from the nearest weather station (Fatick) were used with a set of 34 years. The annual mean is 573 mm of rainfall (Figure 3.6). A year has a rainfall surplus or shortage when its total rainfall is greater or smaller than the set mean, respectively. Nineteen years were with a rainfall surplus and fifteen showed a rainfall shortage. The annual maximal rainfall was registered in 2012 (922.5 mm) and the minimum in 1983 (272.5 mm), the latter coincided with the drought of the 1980s. In general, there is a tendency of rainfall increase with an R^2 of 24.9% from 1980 to 2013 in the zone of study.

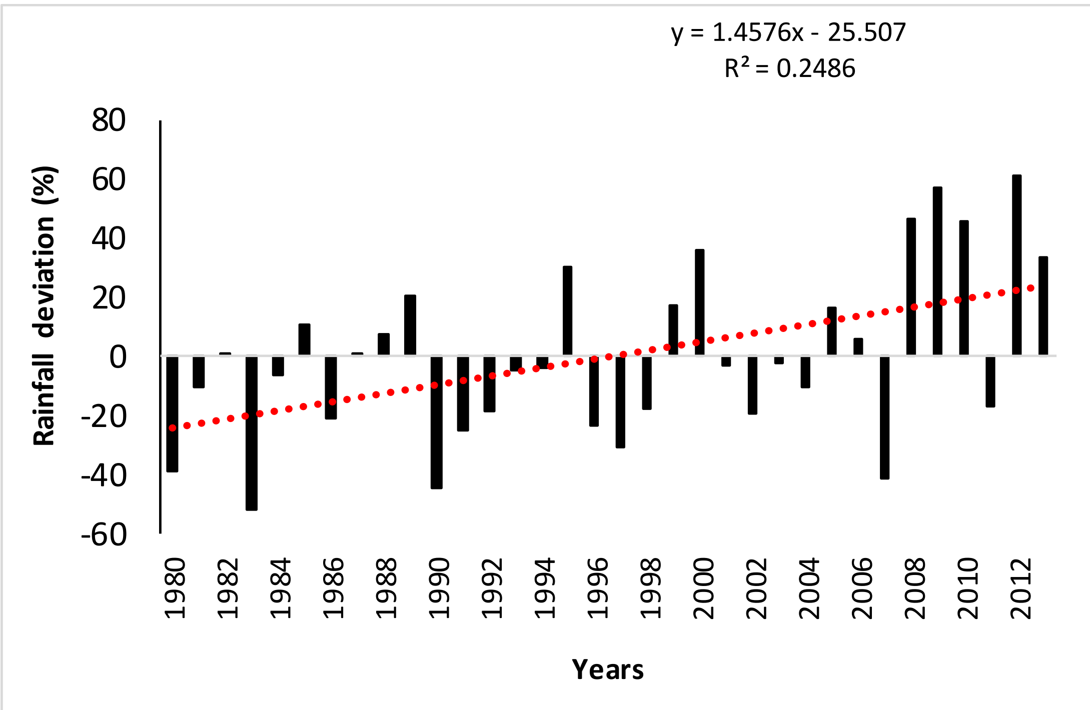

Figure 3.6. Rainfall deviation from the mean (573 mm) of the weather station of Fatick for a period of 34 years (1980-2013)

In this part of Senegal, the rainy season lasts five months, starting in June and ending in October. For the 34 year-period 1980 to 2013, the months with the greatest mean rainfalls were August (230 mm), September (161 mm), and July (110 mm) (Table 3.1).

Table 3.1 Rainfall characteristics of the weather station of Fatick from 1980 to 2013

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Monthly Rainfall Mean (mm)	2.0	1.0	0.0	0.0	0.0	30.0	110.0	230.0	161.0	37.0	0.0	1.0
Standard Deviation	10.1	4.8	0.7	0.0	1.5	30.8	65.2	95.1	72.2	32.2	0.9	5.8
Coefficient of variation	5.5	5.1	5.4	0.0	3.6	1.0	0.6	0.4	0.4	0.9	3.3	4.8
Monthly Maximum	58.0	28.0	4.0	0.0	7.0	123.0	287.0	399.0	359.0	168.0	4.0	33.0
Monthly Minimum	0.0	0.0	0.0	0.0	0.0	0.0	12	47	79	0.0	0.0	0.0
Gap between max and Min	58.0	28.0	4.0	0.0	7.0	123.0	276.0	352.0	280.0	168.0	4.0	33.0
Coefficient of rainfall	0.3	0.2	0.0	0.0	0.1	5.3	19.2	40.1	28.2	6.4	0.0	0.2
Normal Beginning of the season (%)	0.0	0.0	0.0	0.0	0.0	88.2	0.0	0.0	0.0	0.0	0.0	0.0
Early beginning of the season (%)	0.0	0.0	0.0	0.0	21	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Late beginning of the season (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Normal end of the season (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.1	0.0	0.0
Early end of the season (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Late end of the season (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.8	0.0
The wettest month (%)	0.0	0.0	0.0	0.0	0.0	0.0	9	59	32	0.0	0.0	0.0

Landscape units

In Senegal, saline, acid sulfate soils were identified in five landscape units and described by (Sadio and Van Mensvoort, 1993):

(i) saline mudflats known as tannes with mangrove vegetation. Under mangrove vegetation immediately alongside the tidal creeks there are unripe saline sulfidic soils (a succession of sand and unripe clay layers).

(ii) low terraces, 4-4.5 m above mean sea level (MSL), situated close to rivers and creeks, mainly barren. Soils consist of sandy or half ripe fine loamy material poorly drained, and land is inundated during the rainy season with an electrical conductivity of 1: 5 extract varying from 10 to 50 dS m^{-1} during the dry season and a pH between 3.0 to 4.5 in the top 50 cm.

(iii) mid-terraces, 4.5-5.0 m above MSL, some vegetated and some bare. Soil characteristics are similar to low terrace ones, except for the lower interval of both EC (5 dS m^{-1}) and pH (3.5).

(iv) high terraces, 5-6 m above MSL, completely or locally vegetated with an herbaceous vegetation. The soils are identic to those encountered in low and mid-terraces, but are less saline (between 4 and 8 dSm^{-1}).

(v) colluvial slopes, more than 6 m above MSL, transitional between the terraces and the adjacent uplands. Some soils have dark reddish brown concretions in the topsoil with a pH generally between 3.5 and 4.5 and an EC varying from 6 to 40 dS m^{-1}.

It was in this last landscape unit where the field study was conducted in Ndoff in 2014 and 2015.

Experimental design

Millet Cultivars

Three different pearl millet (Pennisetum glaucum L.) cultivars were selected on the basis of traits such as grain yield, quality, variation in height and maturity, and diversity of origin. These germplasms consisted of Gawane, SOSSAT C88, and IBMV 8402. These cultivars were obtained from the Senegalese Institute for Agronomic Research (ISRA) for the two-year field trial conducted in 2014 and 2015 in Ndoff, Senegal.

Experimental design and treatments

Two experiments were arranged in a split-plot design in landscapes of varying salinity (Figure 3.7). The low and high levels are characterized by low electrical conductivity (LEC) and high electrical conductivity (HEC), respectively. The LEC site was at the edge of an upland and the HEC was sited in a transitional zone between high terraces and the upland. Both the LEC and HEC consisted of three main plots, each having three subplots. The main plots were the fertility treatments (control, compost and peanut shell), and the millet cultivars (Gawane, IBMV 8402 and SOSAT C88) were the subplot treatments. Peanut shell and compost were used as local organic amendment. Compost was made of leaves and litter from *Casuarina equisetifolia* L. known as Australian pine tree. Compost is traditionally made with casuarina leaf litter in Dakar and surrounding areas. Organic amendment samples were analyzed as indicated in the greenhouse study.

The main plot size was 5 m x 3 m. It consisted of four rows with an inter-row spacing of 0.9 m. Each row contained six holes (0.9 m spacing between holes), which summed up to 24 holes per main plot. Eight holes were assigned to each cultivar per main plot treatment. Peanut shell and compost were applied at 10 Mg ha^{-1}. The NPK (15-15-15) fertilizer was applied to each plot as a basal treatment at a rate of 150 kg ha^{-1} at planting. Additionally, two applications each of 50 kg ha^{-1} of urea (46-0-0) were applied at 15 and 40 days after planting. All these treatments were applied at the beginning of each growing season.

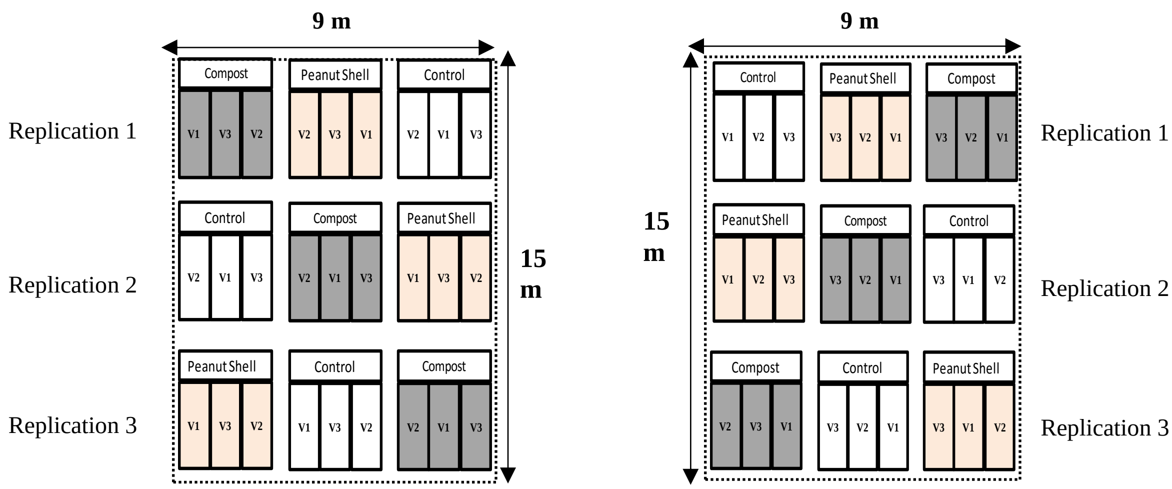

Figure 3.7. Split plot experimental design in Ndoff, Senegal: low salinity (left dotted line), high salinity (right dotted line), compost, peanut shell and control are organic amendment levels (whole plots), V1, V2, and V3 (subplots) are IMBV8402, SOSSAT C88, and Gawane, respectively.

Trial management

The trial was grown with locally appropriate protocols for land preparation, planting date, plot dimensions, plant spacing (0.90 m between holes), row spacing (0.90 m), and fertilizer applications. Prior to 2014, the land had never been cultivated. Therefore, it needed to be prepared. First, shrubs and weeds were manually removed from the land. Secondly, the plots were delineated perpendicularly to the salinity gradient with three replications per salinity levels.

Third, at the beginning of each growing season, amendments were broadly spread in the main plots before tillage by animal traction (Figure 3.8 A; B). After tillage, rows were drawn by a wooden tool. The two former steps were performed in June 2014. In 2014, the experiment was planted on August 16 in both LEC and HEC. In 2015, the experiment was planted on different dates: July 13 (LEC) and August 26 (HEC). The cultivar and amendment treatments were applied to the exact same plots during both years of the study. Two weeks after sowing, plants were thinned and only 3 were left at each hole.

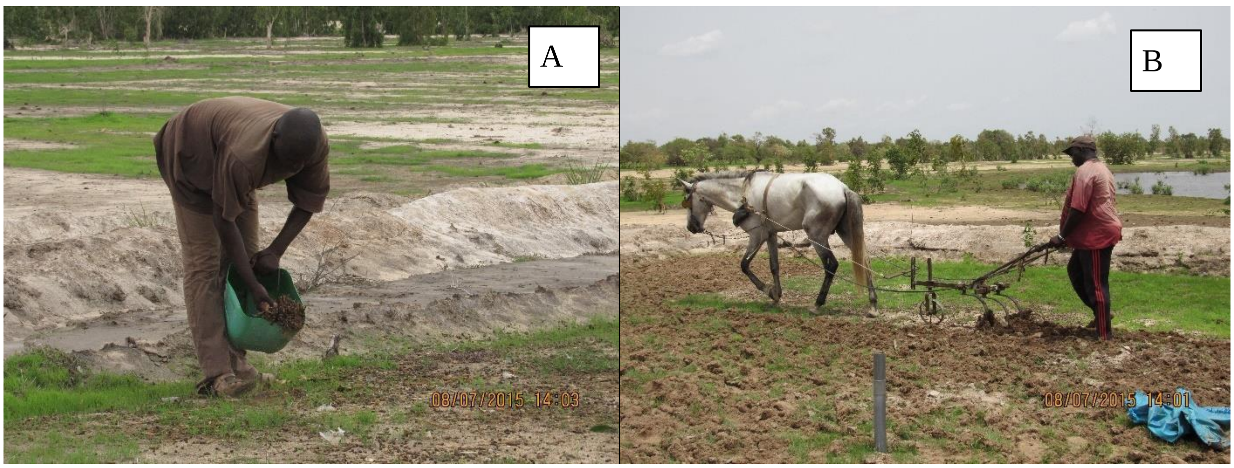

Figure 3.8. Organic amendments being spread (A) and mixed with soil using animal attraction (B) in 2015, Ndoff Senegal. Picture courtesy of Sekouna Diatta.

Sample collection/measurements and processing

Soil sampling

Prior to the experiment establishment, ten soil subsamples were taken from each replication to a depth of 15 cm with push probes in each salinity level to constitute composite samples. After harvest in 2014 (December) and 2015 (November) ten subsamples were also taken from each treatment. Samples were then air-dried and stored in plastic bags at Cheikh Anta Diop University of Dakar until they were shipped to Virginia Tech. Particle size distribution of the soil-sized fraction (% sand, % silt, % clay of the soil-sized fraction) was determined using the pipette method (Gee, et al., 1986). The same soil analysis methods described in the greenhouse studies were also used for nutrients, pH and EC determination.

Plant sampling

Plant height, tiller number, panicle length, diameter and weight, total biomass and grain yield were measured on 4 plants at subplot level for each cultivar. Emergence was assessed during the first week after sowing. Plant height (from ground level to the top of the panicle) and tiller number were measured at the grain filling stage. At harvest, panicle parameters were evaluated, while above ground plant dry matter and grain yield were air-dried and weighed.

Statistical analysis

Data were statistically analyzed using analysis of variance technique appropriate for split plot design (plant) and randomized complete block design (soil) using JMP Pro 12.0.1. Main and interaction effects were separated for multiple comparison by Tukey HSD at 0.05 level of probability, if the P-values were significant. Repeated measurement analyses of variance (ANOVA) with the factors as seedling emergence, plant height, total and productive tillers were conducted in both low and high salinity plots.

3.4. Results

3.4.1. Greenhouse Studies

Soil characteristics before planting

The Old Hickory soil had a loamy sand texture (Table 3.2) and a pH of 5.5. Total N and total C were 300 and 3600 mg kg^{-1}, respectively. The concentrations of extractable P, K, Ca and Mg were 27, 44, 255 and 21 mg kg^{-1}, respectively. The textural class of the mixture WSCB was sandy (88.5% of sand) with more total N (385 mg kg^{-1}) and total C (3,449 mg kg^{-1}) than Old Hickory. The extractable macronutrients were 8, 35, 263 and 112 mg kg^{-1} for P, K, Ca and Mg, respectively. The WSCB mixture pH was lower (4.4). These textures are typically low in organic matter, low in CEC and permeable. Nutrients such as P and K are typically low and fertilizer application is needed (DCR, 2014).

Greenhouse Experiment 1

Effects of lime and EC on plant growth

Salinity can negatively impact plant physiological response and production (Syvertsen and Garcia-Sanchez, 2014); e.g., via inhibition of plant's ability to assimilate water. Three-way analysis of variance for germination and early plant development data is presented in Table 3.3. There were no significant Lime*EC*Cultivar interaction effects on seedling emergence and growth. Root dry matter was affected by Lime*EC and Cultivar*EC interactions. Lime affected shoot height which was higher in the media with a pH of 6.2 (Table 3.2), and EC affected all traits except seedling emergence.

Table 3.2. Lime main effects on shoot height of 10-day pearl millet seedlings. No lime: pH = 5.5, Lime: pH = 6.2. Values followed by the same letter are not significantly different ($\alpha = 0.05$).

Lime	**pH**	**Shoot height (cm)**
- Lime	5.5	17.6[b]
+ Lime	6.2	19.2[a]

Effects of lime*EC interactions on root dry matter

The soil used in this experiment was strongly acidic (pH = 5.5) and was limed to raise the pH to 6.2. in combination with five levels of salinity. Before sodium chloride and calcium chloride application, soil EC was 0.3 dS m^{-1}.

Table 3.3. Properties of soils used in the two greenhouse studies experiments. Textural class was determined from particle size analysis measured via pipette method. C and N data were determined via combustion. Mehlich I extractable nutrients and pH are part of the Virginia Tech Soil Testing Laboratory routine analyses. WSCB (washed sand, Cheatham and Bojac) is a mixture of a washed sand (85%), a dredge material (Cheatham, 10%) and Bojac series (5%), while Old Hickory is Orangeburg Series.

	Particle Size			**pH (1:2)**	**Textural class**	**Total C and N**		**Mehlich I**			
Soils	**Sand** (g kg^{-1})	**Silt** (g kg^{-1})	**Clay** (g kg^{-1})			**TN** (mg kg^{-1})	**TC** (mg kg^{-1})	**P** (mg kg^{-1})	**K** (mg kg^{-1})	**Ca** (mg kg^{-1})	**Mg** (mg kg^{-1})
WSCB	885	48	67	4.4	Sand	385	3,449	8	35	263	112
Old Hickory	830	100	70	5.5	Loamy Sand	300	3,600	27	44	255	21

Table 3.4. ANOVA table of treatments and plant parameters (P-value) for all salinity levels. Lime: - Lime (pH = 5.5) and + Lime (pH = 6.2); Electrical Conductivity (EC): 0.3, 2.1, 4.2, 5.2 and 6.3 dS m^{-1}; Cultivar: IBMV 8402, SOSAT C88, ICMV-IS 88102, IKMP1, IKMP2, IKMV 8201 and GAWANE; DAS: days after sowing. ns: non-significant.

	df	**Emergence 7 DAS**	**Shoot Height**	**Root Length**	**Shoot Dry Matter**	**Root Dry Matter**	**No. of Leaves**
Lime	1	ns	0.0002	ns	ns	0.0003	ns
EC	4	ns	<.0001	ns	0.0043	<.0001	<.0001
Cultivar	6	<.0001	<.0001	0.0003	<.0001	<.0001	<.0001
Lime*EC	4	ns	ns	ns	ns	0.0005	ns
Lime*Cultivar	6	ns	ns	ns	ns	ns	ns
Cultivar*EC	24	ns	ns	ns	ns	0.0311	ns
Cultivar*EC* Lime	24	ns	ns	ns	ns	ns	ns

The application of lime or liming materials to acid soil might mitigate soil acidity while increasing soil EC would decrease root dry matter. The Lime*EC interaction effects on root dry matter were significant (Table 3.4). In low EC (0.3 and 2.1 dS m^{-1}), plants performed better in low pH (5.5), suggesting that the lime might exacerbate the soil EC, which in turn, decreased root dry matter. In media with EC greater than 4.2 dS m^{-1}, there were no significant effects on root dry matter between limed and no limed media, probably due to an increasing EC effect resulting from both lime and EC. This means that when EC levels are high, mitigating soil acidy does not increase root dry matter.

Table 3.5. Lime*EC interaction effects on root dry matter of 10-day pearl millet seedlings. Lime: - Lime (pH = 5.5), + Lime (pH = 6.2); Electrical Conductivity, EC (dS m^{-1}):0.3, 2,1, 4.2, 5.2 and 6.3. Values followed by the same letter are not significantly different ($\alpha = 0.05$).

Level	**Root dry matter (mg)**
- Lime, 0.3	42^{a}
+ Lime, 0.3	29^{bcd}
- Lime, 2.1	36^{ab}
+ Lime, 2.1	24^{cd}
- Lime, 4.2	32^{abc}
+ Lime, 4.2	33^{abc}
- Lime, 5.2	29^{bcd}
+ Lime, 5.2	32^{bc}
- Lime, 6.3	26^{bcd}
+ Lime, 6.3	22^{d}

Effects of Cultivar*EC interactions on root dry matter

As discussed above, soil EC at high levels can negatively affect plant growth, particularly root dry matter, and this might vary among cultivars. Cultivar*EC interaction effects on root dry matter were significant, suggesting that some cultivars were more sensitive to EC than others (Figure 3.9). Regression analysis of the data by cultivars yielded varying linear fits. Increasing soil EC, discriminated pearl millet cultivars in three groups.

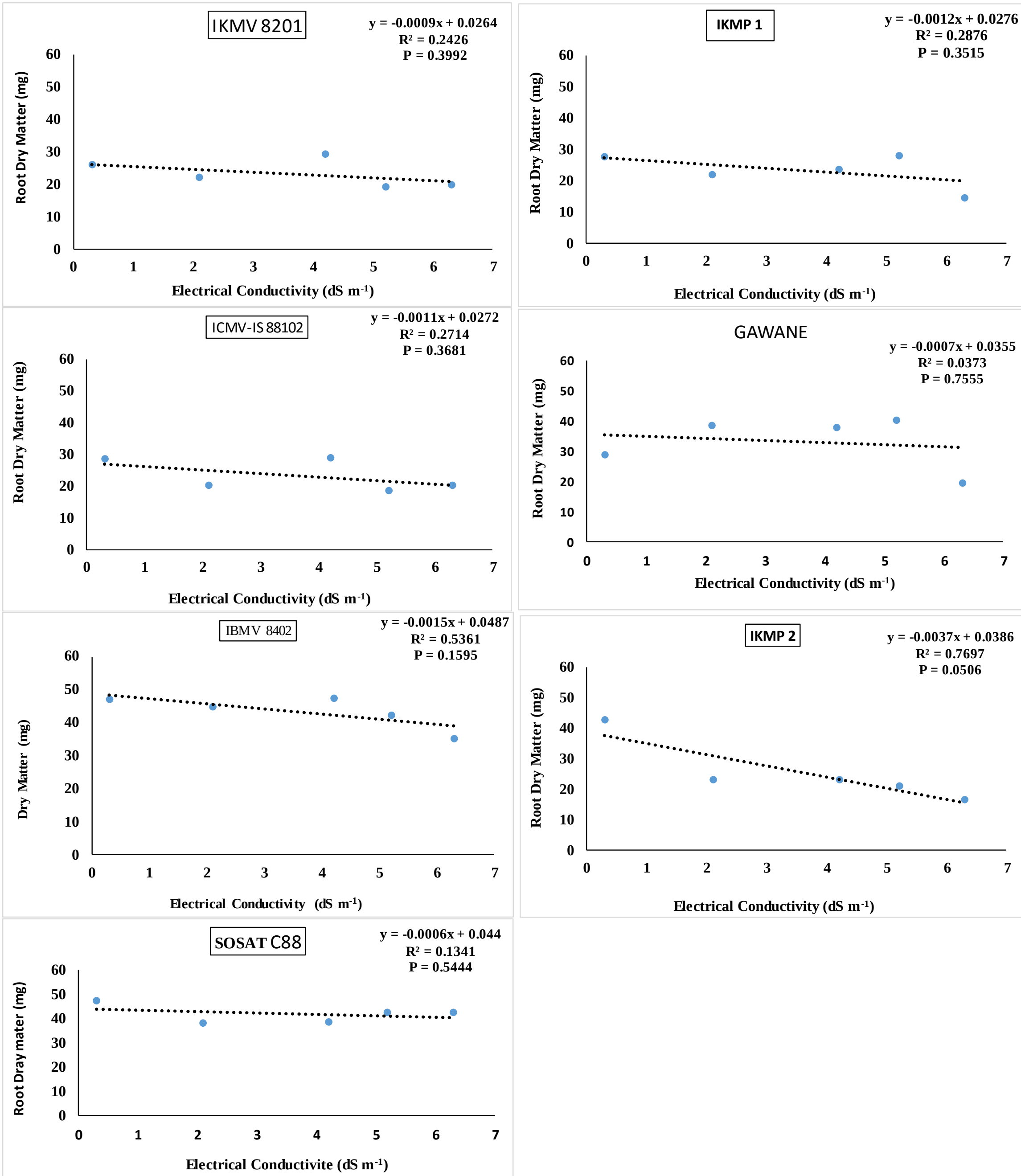

Figure 3.9. EC*Cultivar interactions on root dry matter of pearl millet 10-day-seedlings.

The most sensitive were cultivars IBMV 8402 and IKMP 2 with 53.6 and 77.0% root dry matter decrease, respectively, explained by the EC. The root dry matter difference between the lowest and the highest EC levels were 12 and 26 mg for cultivars IBMV 8402 and IKMP 2, respectively. The second group constituents were IKMV 8201, ICMV-IS 88102 and IKMP 1 with 24.3, 27.1 and 28.8% of root dry matter decrease, respectively. Cultivars SOSAT C88 and GAWANE showed 13.4 and 3.7% of root dry matter decrease, respectively, suggesting that they were more tolerant to salinity.

Effects of EC on height, shoot dry matter and number of leaves and of pH on shoot height

Electrical conductivity had significant effects on shoot height and dry matter (Figures 3.10; 3.11). Plant height and shoot dry matter decreased as EC increased. Salinity stress affected plant growth in two ways. Under saline conditions, plant growth is inhibited by osmotic effects on water uptake, which results in water deficit for the plants. When salt accumulates in the root zone, the excess of a specific ion, for instance Na^+ or Cl^-, can cause toxicity, which in turn can induce nutritional disorders (Khatoon, et al., 2010). Salinity causes many adverse effects on the morphology, anatomy and physiology of pearl millet (Hussain, et al., 2010). Hussain, et al. (2008) reported that height of pearl millet decreased with increasing salinity. The number of leaves was more sensitive to salinity with 92.5% of decrease explained by EC (Figure 3.12). It significantly decreased with the increasing EC. Consequently, sensitive cultivars would be expected to have lower biomass than tolerant cultivars because at this stage leaves constitute an important part of aboveground biomass. Also, as expected an increase of shoot height occurred with pearl millet optimum pH (6.2) (Table 3.5).

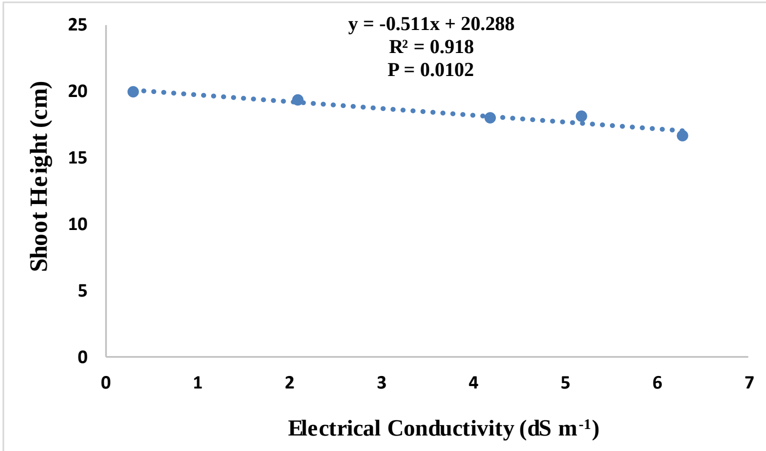

Figure 3.10. Effects of EC on shoot height of 10-day pearl millet seedlings averaged across all seven pearl millet cultivars and lime rates.

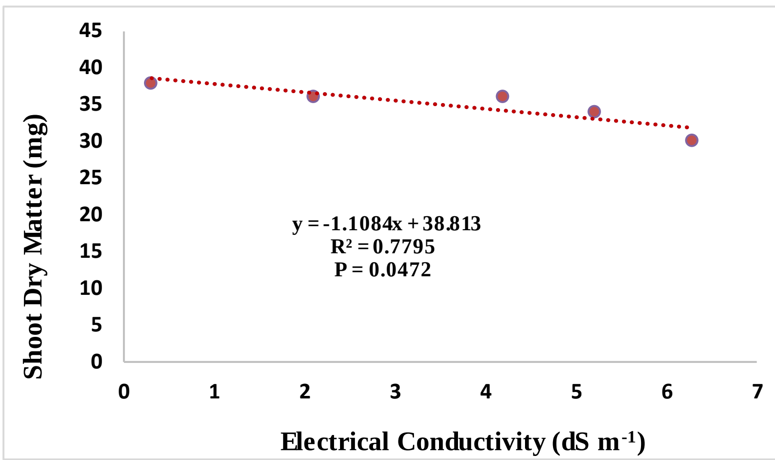

Figure 3.11. Effects of EC on shoot dry matter of 10-day pearl millet seedlings averaged across all seven pearl millet cultivars and lime rates.

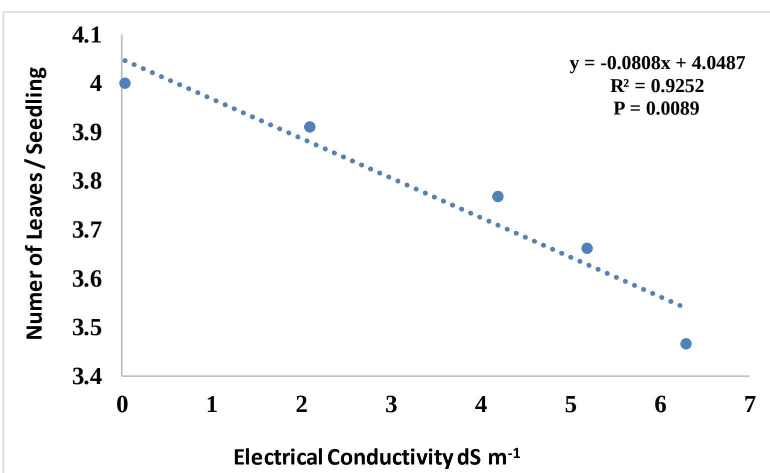

Figure 3.12. Effects of EC on the number of leaves of 10-day pearl millet seedlings averaged across all seven pearl millet cultivars and lime rates.

Greenhouse Experiment 2

Characteristics of fertilizers and phosphogypsum

Characteristics of fertilizers used in this study are summarized in Table 3.6. Each organic fertilizer, except peanut shell from Senegal had a C: N ratio less than 20: 1; thus, the composts were expected to provide net N mineralization. The manure-based compost contains, as expected, higher concentrations of P and K than the plant-based composts. All composts have pH of 7.3 or higher and would be expected to raise the soil pH more than the peanut shell. Unlike composts, PG is ultra-acidic (pH = 2.24) and would lower the soil pH (Table 3.7). Its EC is equal to 5.8 dS m^{-1} and would be expected to increase soil EC.

Effects of fertilizers and phosphogypsum on pH, EC, P and Ca

Fertilizer and PG characteristics mentioned above affected soil chemical properties. The data in the ANOVA Table 3.8 show significant Fertilizer*PG interaction effects on soil pH, EC, P and Ca. Phosphogypsum main effects were also significant for these parameters while fertilizer main effects were significant for all soil parameters. Organic matter is a potential source of plant macro and micro-nutrients such as N, P, K, Mg, Mn, Fe, Cu and S released in the soil solution during both cation exchange and mineralization processes. Before application, soil, PG and fertilizers pH were ultra-acidic (2.2) and moderately acidic to slightly alkaline (6.0-7.8), respectively. Six weeks after application, Fertilizer*PG interaction effects on pH, EC, P and Ca were significant (Table 3.9). The higher the pH of the fertilizers, the higher the soil pH due to organic matter buffering, although the ultra-acidic PG pH. This buffering effects were more pronounced CDMC, PW and PSS66. The high EC (5.8 dS m^{-1}) of the PG explained its EC-raising effects on fertilizers. All fertilizer EC increased when the PG was added to them. The quality of compost is determined by its physical, chemical and biological characteristics and the increase of EC in compost is correlated to the present of soluble salts. There was little variation in EC among fertilizers with PWC having the highest EC level without PG, suggesting it had more soluble salts. Phosphogypsum had also significant effects on P and Ca. This was not surprising because PG has a high Ca content and often P as impurity. Based on all above, adding PG would lower the soil pH, exacerbate its EC and improve its Ca and P contents, which might affect plant responses.

Effects of fertilizers on C, N, K and Mg

Fertilizer main effects were significant for C and N as well as K and P. In fact, organic matter is a good source of nutrients for plant growth such as N, P, K, and Ca. With their relatively stable source of organic matter, compost products slowly release nutrients in the medium. This explained why six weeks after fertilizer application, PWC, CDMC, PSS66 and CS48 had the highest N, P, K and Mg contents in the media (Table 3.10). The low content of these elements in the other fertilizers (control, NPK, PSS5, and CS5) was probably due to the plant uptake.

Table 3.6. Characteristics of organic amendments used in both greenhouse and field studies. Amendments consist of compost from Senegal (CS), peanut shell from Senegal (PSS), Cowpie dairy manure compost (CDMC) and Prince William County yard waste compost (PWC).

Amendments	**pH (1:1)**	**Total solids (g kg^{-1})**	**Carbon (g kg^{-1})**	**Total N (g kg^{-1})**	**Organic- N (g kg^{-1})**	**NH4-N (mg kg^{-1})**	**Total PAN (g kg^{-1})**	**C: N Ratio**	**P (g kg^{-1})**	**K (g kg^{-1})**	**Ca (g kg^{-1})**	**Mg (g kg^{-1})**
CS	7.3	575.3	164	10.9	10.5	400	1.96	17	1.17	1.74	20.80	3.78
CDMC	7.7	725.3	269	24.0	23.3	731	4.18	11	8.17	29.60	29.40	10.60
PSS	6.0	904.0	315	9.8	9.1	664	0.66	35	0.72	6.54	5.38	1.13
PWC	7.5	503.0	290	14.2	13.8	437	1.80	18	1.72	9.15	21.90	4.87

Table 3.7. Characteristics of phosphogypsum (PG) used in the second greenhouse study (pH and EC saturated paste).

	pH	**EC (dS m^{-1})**
PG	2.24	5.80

Table 3.8. Effects of fertilizers and phosphogypsum on Washed Sand Cheatham and Bojac mixture soil properties six weeks after greenhouse study 2. **ns:** non-significant.

	pH (1:2)	**ECe (dS m^{-1})**	**C-N Analysis**			**Mehlich I Extract**			
			N (g kg^{-1})	***C (g kg^{-1})***	***C: N Ratio***	***P (mg kg^{-1})***	***K (mg kg^{-1})***	***Ca (g kg^{-1})***	***Mg (mg kg^{-1})***
Fertilizers \ P-value	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
PG \ P-value	<.0001	<.0001	ns	ns	ns	<.0001	ns	<.0001	ns
Fertilizer*PG\ P-value	0.0005	<.0001	ns	ns	ns	0.0176	ns	0.0321	ns

Table 3.9. Effects of Fertilizer*PG interactions on pH, EC, P and Ca. pH of 1: 1, water: soil, EC of saturated paste and Mehlich I extractable P and Ca. *Values followed by the same letter in a column are not significantly different (α = 0.05).*

	pH	**EC (dS m^{-1})**	**P (mg)**	**Ca (g)**
0,CDMC	6.71^{a}	2.98^{fgh}	28.3^{b}	0.48^{e}
0,PWC	6.51^{ab}	3.54^{d}	16.7^{ghi}	0.68^{d}
0,PSS66	6.22^{bc}	2.75^{h}	13.8^{ij}	0.44^{e}
8.5,CDMC	6.12^{cd}	5.05^{a}	39.6^{a}	1.85^{ab}
0,CS48	6.11^{cd}	2.95^{fgh}	15.8^{hij}	0.69^{d}
8.5,CS48	6.06^{cde}	4.10^{c}	25.3^{bc}	1.89^{a}
8.5,PWC	6.02^{cdef}	4.43^{b}	24.2^{cd}	2.01^{a}
8.5,PSS66	5.85^{defg}	4.01^{c}	19.6^{efg}	1.59^{c}
0,Control	5.73^{efg}	3.33^{de}	12.3^{j}	0.39^{e}
0,CS5	5.69^{fg}	3.04^{efg}	14.9^{hij}	0.43^{e}
0,PSS5	5.67^{fg}	2.77^{gh}	12.3^{j}	0.37^{e}
8.5,CS5	5.61^{g}	4.02^{c}	22.7^{cde}	1.68^{bc}
8.5,Control	5.58^{g}	4.25^{bc}	20.9^{def}	1.71^{bc}
8.5,PSS5	5.56^{g}	4.15^{bc}	20.6^{ef}	1.70^{bc}
0,NPK	5.54^{g}	3.06^{ef}	17.5^{fgh}	0.39^{e}
8.5,NPK	5.50^{g}	4.09^{c}	25.5^{bc}	1.65^{c}

Table 3.10. Effects of fertilizer on soil C, N, C: N, K and Mg. *Values followed by the same letter in a column are not significantly different (α = 0.05).*

	N (g kg^{-1})	**C (g kg^{-1})**	**C: N Ratio**	**K (mg kg^{-1})**	**Mg (mg kg^{-1})**
Control	0.4^{c}	3.7^{e}	9^{d}	24^{c}	112^{de}
CDMC	0.7^{ab}	6.2^{cd}	9^{d}	173^{a}	140^{bc}
CS5	0.4^{c}	3.4^{e}	9^{d}	20^{c}	112^{e}
CS48	0.6^{b}	7.0^{c}	12^{c}	31^{c}	155^{ab}
NPK	0.4^{c}	3.3^{e}	8^{d}	22^{c}	103^{e}
PSS5	0.4^{c}	4.5^{de}	11^{c}	26^{c}	110^{e}
PSS66	0.7^{ab}	15.2^{a}	21^{a}	150^{ab}	128^{cd}
PWC	0.8^{a}	10.4^{b}	13^{b}	81^{bc}	158^{a}

Effects of fertilizers and phosphogypsum on plant variables

Fertilizer*PG interaction effects on NDVI were significant while fertilizer main effects were significant for both NDVI and plant dry biomass (Table 3.11). The correlation between N and NDVI is well known. The NDVI was highest for PSS66 regardless of the PG addition (Table 3.13). Also, treatment PSS66 was among those that had the total N at the end of the experiment (Table 3.10), and recorded the highest dry biomass in both shoot and root (Table 3.12). In fact, under non-limiting water supply, the N status of a crop is the major factor controlling the rate of biomass accumulation (Jensen, et al., 1990). Thus, the high NDVI values of PSS66 were in accordance with plant biomass and total N in this treatment.

Table 3.11. ANOVA table of cultivar SOSAT C88 plant responses to fertilizer and phosphogypsum (PG) application in the greenhouse study 2. **S DW:** Shoot dry weight, **R DW:** Root dry weight.

	Emergence (%)	**NDVI *Day 45***	**Biomass (g/plant)**	
			SDW	***RDW***
Fertilizers / P-value	ns	<.0001	<.0001	<.0001
PG / P-value	ns	<.0186	ns	<.0001
Fertilizer*PG / P-value	ns	0.0190	ns	ns

Table 3.12. Responses of cultivar SOSAT C88 plants to fertilizer and phosphogypsum (PG) application in greenhouse study 2. Values followed by the same letter in a column are not significantly different (α = 0.05). **S DW:** Shoot dry weight, **R DW:** Root dry weight.

	Emergence (%)	**Biomass (g/plant)**	
Fertilizers		***SDW***	***RDW***
Control	94	0.49^{d}	0.23^{d}
CDMC	94	0.88^{bc}	0.33^{cd}
CS5	95	0.76^{cd}	0.40^{bc}
CS48	94	0.76^{cd}	0.33^{cd}
NPK	91	1.10^{b}	0.48^{ab}
PSS5	93	0.85^{bc}	0.34^{bcd}
PSS66	93	1.45^{a}	0.59^{a}
PWC	88	0.82^{bc}	0.32^{cd}
Phosphogypsum			
+ PG	92	0.85	0.31^{b}
- PG	92	0.92	0.44^{a}

Table 3.13. Fertilizer*PG interaction effects on NDVI of cultivar SOSAT C88 plants six weeks after application in greenhouse study 2. Values followed by the same letter are not significantly different (α = 0.05).

Fertilizer	**-PG**	**+PG**
PSS66	0.52^{a}	0.54^{a}
PSS5	0.34^{b}	0.42^{b}
CDMC	0.35^{b}	0.42^{b}
NPK	0.40^{b}	0.35^{b}
CS5	0.35^{b}	0.38^{b}
PWC	0.38^{b}	0.37^{b}
Control	0.35^{b}	0.36^{b}
CS48	0.35^{b}	0.35^{b}

Effects of fertilizers, time, and phosphogypsum on plant height

Two-way interaction effects of Time*PG, Time*Fertilizer and PG*Fertilizer were significant with respect to plant height during the six weeks of measurement (Table 3.14).

Table 3.14. Repeated measure ANOVA table of the effects of fertilizers, phosphogypsum PG and time on plant height. **ns:** non-significant.

Treatments	Plant height (cm)
Time	<.0001
PG	<.0001
Time*PG	0.0361
Fertilizer	<.0001
Time*Fertilizer	0.0003
PG*Fertilizer	0.0105
Time*PG*Fertilizer	ns

Depending on the interactions, the data showed that:

- During the two first weeks, PG had no effects on plant height. However, it decreased plant height 4 and 6 weeks after sowing (Figure 3.13).
- PG decreased plant height only for CDMC, PSS5 and CS5 (Table 3.15);
- There was no difference among fertilizers during the two first weeks, the treatment control being different from all fertilizers except NPK, CS5, PSS66 and PSS5 (30 DAS). Forty-five DAS, only NPK and PWC had higher plant height than the control (Table 3.16). These two fertilizers might have more available N 4 weeks after sowing.

The decrease of plant height was probably due to the EC increase in pots amended with PG since it was above 4.0 ds m^{-1}.

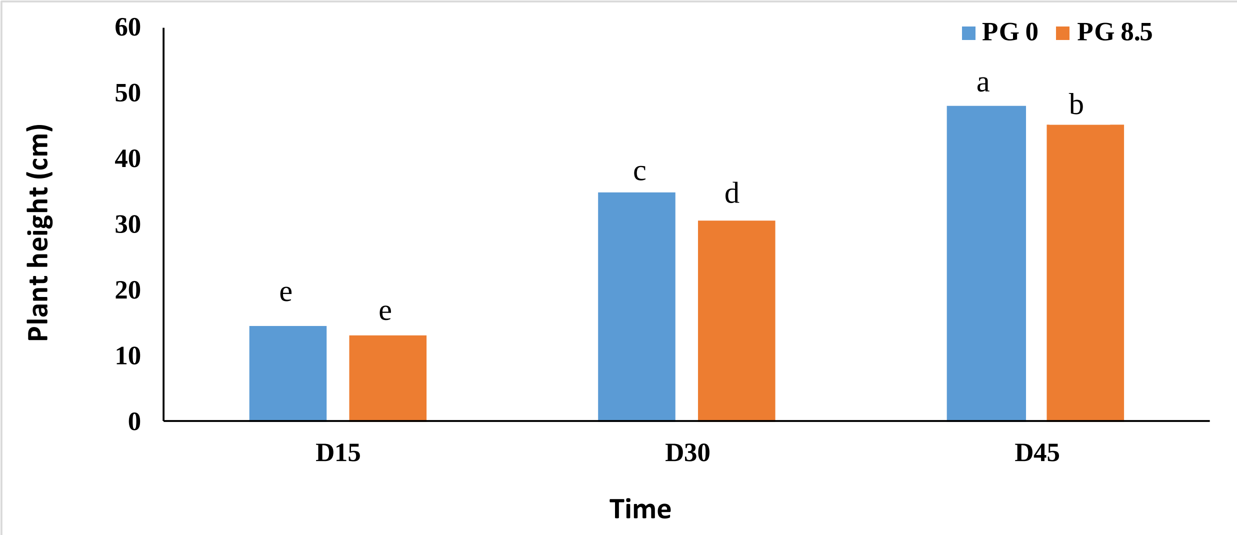

Figure 3.13. Time*PG interaction effects on plant height of cultivar SOSAT C88 six weeks after application in greenhouse study 2. Values followed by the same letter are not significantly different (α = 0.05).

Table 3.15. Fertilizer*PG interaction effects on plant height of cultivar SOSAT C88 six weeks after application in greenhouse study 2. Values followed by the same letter are not significantly different (α = 0.05).

Fertilizer	**- PG**	**+PG**
CDMC	35.2^{a}	30.7^{bcd}
Control	30.2^{bcde}	26.4^{de}
CS48	33.6^{ab}	32.4^{abc}
CS5	34.1^{ab}	28.8^{cde}
NPK	33.7^{ab}	32.4^{abc}
PSS5	30.7^{bcd}	25.6^{e}
PSS66	28.9^{cde}	26.5^{de}
PWC	34.0^{ab}	34.4^{ab}

Table 3.16. Fertilizer*Time interaction effects on plant height of cultivar SOSAT C88 six weeks after application in greenhouse study 2. Values followed by the same letter are not significantly different (α = 0.05).

	Time (days)		
Fertilizer	**15**	**30**	**45**
NPK	13.7^{h}	34.6^{de}	50.9^{a}
PWC	15.0^{h}	37.7^{cd}	49.9^{a}
CS48	15.7^{h}	35.4^{d}	47.9^{ab}
CDMC	14.4^{h}	36.7^{d}	47.8^{ab}
CS5	14.2^{h}	34.0^{def}	46.2^{ab}
PSS5	11.1^{h}	28.2^{fg}	45.2^{ab}
Control	12.6^{h}	29.3^{efg}	42.9^{bc}
PSS66	13.5^{h}	26.6^{g}	42.9^{bc}

3.4.2. Field Study

Initial soil properties in both low and high salinity plots

Soil particle size analysis showed that the experiment was set in a coarse-textured soil in Ndoff (Table 3.17), suggesting large pores, low CEC and low water holding capacity. Sandy soils are typically low in organic matter and fertility. The electrical conductivity was high in low salinity plot (4.98 dS m^{-1}) and extremely high in the high salinity plot. Both salinity plots had pH that limited plant growth. Soils were strongly acidic with pH of 4.2 and 4.0 in low salinity and high salinity plots, respectively. The buffer indexes in both plots were similar (BpH of 6.2), indicating the same lime requirement. Low fertility, acidity and salinity are detrimental to crop production and quality (Lei, et al., 2016, Nath, et al., 2016) and application of organic fertilizers have been shown to increase soil biological, physical, and chemical properties (Glaser, et al., 2002).

Effects of organic fertilizers on soil chemical properties

There were no significant effects of fertilizers on pH, EC and indices of fertility in either salinity site soil (Tables 3.18; 3.20). There were significant effects of year on all soil variables measured, except pH, in both low and high salinity plots. Soluble salt concentrations in soil and, thus, EC levels, should be expected to increase from the addition of N, P and K fertilizers and from the decomposition of soil organic matter. The saturated paste extract EC decreased in the low salinity site soil from 2.9 dS m^{-1} in 2014 to 0.6 dS m^{-1} in 2015 and in the high salinity site soil from 28 dS m^{-1} in 2014 to 9 dS m^{-1} in 2015 (Tables 3.19; 3.21). The EC decrease was likely caused by leaching of soluble salts (Mohamed, et al., 2007) during the wetter 2015 season (Fig. 3.14). Total rainfall in 2014 and 2015 was 417 mm and 698, respectively. In addition, the rainy season started in mid-August in 2014 versus mid July in 2015. Associated with the lower EC in 2015 was a decrease in concentration of macronutrients (P, K, Ca and Mg), C and N. Such elements occur in soils as ions, and their lowered concentrations are directly correlated to reduced EC.

The application of peanut shells and compost did not raise soil pH as expected. The pH-raising benefits of basic cations was likely cancelled by the acid-forming nitrification reactions as organic N was converted to ammonium and then nitrate N. The high leaching rainfall in 2015 likely leached both basic and acid cations from the 0-15 cm soil layer.

Table 3.17. Particle size analysis of the soil in low and high salinity plots in Ndoff.

Particle Size name	Low Salinity Plot	High Salinity Plot
Very Coarse Sand (%)	0.2	0.2
Coarse Sand (%)	0.6	1.7
Medium Sand (%)	7.4	12.6
Fine Sand (%)	50.0	51.1
Very Fine San (%)d	30.3	24.3
Total Sand (%)	88.5	89.9
Coarse Silt (%)	4.6	3.3
Medium Silt (%)	2.8	2.5
Fine silt (%)	0.3	0.7
Total Silt (%)	7.7	6.5
Total Clay (%)	3.8	3.6
Textural Class (%)	Sand	sand
EC (dS m^{-1})	5.0	34.6
pH	4.2	4.0
BpH	6.2	6.2

Table 3.18. Repeated measure ANOVA table of the effects of fertilizers and time on pH, EC and soil fertility in low salinity plot after harvest in 2014 and 2015 in Ndoff, Senegal.

	pH (1:2)	ECe (dS m^{-1})	Mehlich I				C and N Composition		
			P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	C (g/kg)	N (g/kg)	C: N ratio
Fertilizer (P-value)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
Year (P-value)	ns	0.0047	<0.0001	0.0035	0.0037	0.0001	0.0200	0.0179	ns
Fertilizer*Year P-value	ns	ns	ns	ns	ns	ns	ns	ns	ns

Table 3.19. Year main effects on pH, EC and soil fertility in low salinity plot after harvest in 2014 and 2015 in Ndoff, Senegal. For each parameter, values followed by the same letter are not significantly different (α = 0.05).

	pH (1:2)	ECe (dS m^{-1})	Mehlich I				C and N Composition		
			P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	C (g/kg)	N (g/kg)	C: N ratio
2014	5.0 [a]	2.9[a]	4.0[a]	51[a]	199[a]	44[a]	5.2[a]	0.52[a]	10 [a]
2015	4.8 [a]	0.6[b]	1.0[b]	32[b]	113[b]	19[b]	3.3[b]	0.37[b]	9 [a]

Table 3.20. Repeated measure ANOVA table of the effects of fertilizers and time on pH, EC and soil fertility in high salinity plot after harvest in 2014 and 2015 in Ndoff, Senegal.

	pH (1:2)	**ECe (dS m^{-1})**	**Mehlich I**				**C-N Analysis**		
			P (mg/kg)	**K** (mg/kg)	**Ca** (mg/kg)	**Mg** (mg/kg)	**C** (g/kg)	**N** (g/kg)	**C: N ratio**
Fertilizer (P-value)	ns	ns	ns	ns	ns	ns	ns	ns	ns
Year (P-value)	ns	0.0494	<.0001	ns	0.0267	0.0401	ns	0.0341	ns
Fertilizer*Year (P-value)	ns	ns	ns	ns	ns	ns	ns	ns	ns

Table 3.21. Year main effects on pH, EC and soil fertility in high salinity plot after harvest in 2014 and 2015 in Ndoff, Senegal. For each parameter, values followed by the same letter are not significantly different (α = 0.05).

	pH (1:2)	**ECe (dS m^{-1})**	**Mehlich I**				**C-N Analysis**		
			P (mg/kg)	**K (mg/kg)**	**Ca (mg/kg)**	**Mg (mg/kg)**	**C (g/kg)**	**N (g/kg)**	**C: N ratio**
2014	4.6 ^{a}	28^{a}	3.4^{a}	130	161^{a}	249^{a}	3.8	0.40^{a}	9 ^{a}
2015	4.8 ^{a}	9^{b}	1.3^{b}	78	112^{b}	71^{b}	2.8	0.29^{b}	9 ^{a}

Effects of organic fertilizers on plant responses

Plant responses to organic amendment application evaluated in 2014 and 2015 were analyze and presented in two categories. Seedling emergence, plant height, total and productive tillers were considered as repeated measures. Panicle length, diameter and weight, biomass and grain yield were not evaluated in 2014 because the nearly mature plants were accidentally grazed by cattle.

Seedling Emergence

Time and fertilizer main effects on seedling emergence were significant (Tables 3.22; 3.23 and 3.24). Seed germination and seedling emergence are the two first steps of crop growth. A successful transition seed-to-seedling allows adequate stand establishment under different environmental conditions, especially under condition of stress, such as salt stress (Silva, et al., 2016). This transition from a quiescent dry seed to an actively growing photoautotroph seedling is a crucial trait for plant development. Seedling stage has been used as a predictor of grain nitrogen yield in wheat. In a field whose soil characteristics are described above, we studied the effects of organic fertilizers on the seedling emergence of three millet cultivars (SOSAT C88, Gawane and IBMV 8402) during 2 years and the 2 formers performed best. Seedlings emerged better in treatment with peanut shells (87%) although there were no differences in pH and EC among treatments. This high percentage might be due to other soil properties not measured in our study such as soil aeration and water holding capacity, which are two factors important in seed germination Seedling emergence was also affected by time. The percentage of emergence was higher in 2015, likely due to reduced EC in 2015. Emergence increased from 71 to 89% in low salinity plot. Because pH and rainfall were equal in both low and high salinity plots, we expected EC to be limiting to plant growth in the high salinity site plot, where EC was still high despite the abundant rainfall. There were significant Time*Fertilizer interaction effects on seedling emergence (Table 3.25). In 2015 seedling emerged better with compost and control (Table 3.26). As in the low salinity plot, peanut shell improved emergence regardless of the year.

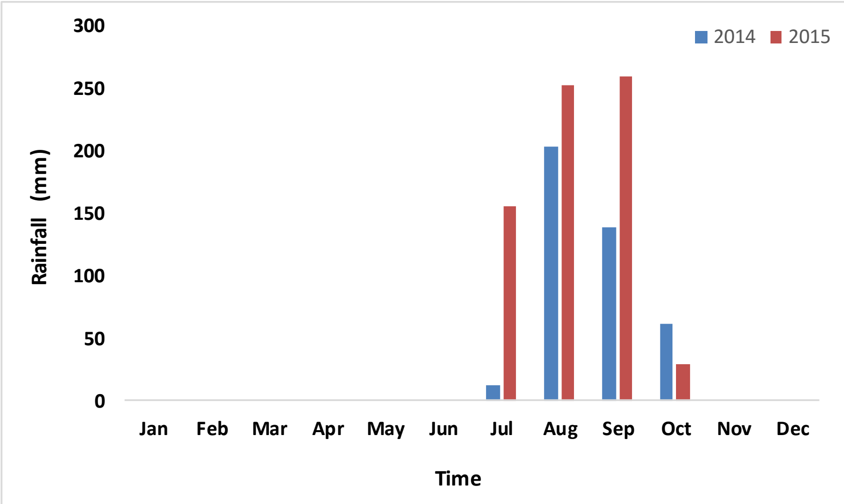

Figure 3.14. Monthly rainfall during the two growing seasons (2014 and 2015) in Ndoff, Senegal.

Plant height

The adverse effect of salinity on pearl millet growth, biomass and grain yields has been demonstrated (Reiad, et al., 2014), along with the ability of organic matter for improving soil biological, chemical and physical properties has the ability to alleviate this detrimental effect (Rahi, et al., 2014). Under low salinity conditions, plant height was only affected by the time (Table 3.22 and 3.24). Plants were 40 cm taller in 2015. In contrast, only fertilizers affected plant height in high salinity plot (Table 3.5 and 3.27). The plant heights in the 2014 and 2015 high salinity plots were similar, probably due to salt stress even under the higher leaching rainfall amounts of 2015. The EC remained high (9 dS m^{-1}) despite the rainfall dilution and presumed salt leaching. In the low salinity, the rainfall was enough to consistently lower the EC in 2015. As a result, plants were taller. Plant height in the high salinity plot was greater with peanut shells and compost than in the control treatment. Given that there was no pH, EC and fertility difference among treatments, an improvement of some soil physical properties that were not evaluated (decrease of bulk density, more porosity and water holding capacity) may possibly explain the outperformance of plant in peanut shell amendment.

Table 3.22. Repeated measure ANOVA table of the effects of fertilizers, cultivars and time on plant responses in low salinity plot after harvest in 2014 and 2015 in Ndoff, Senegal.

	Emergence (%)	**Plant height (cm)**	**Total Tillers**	**Productive Tillers (%)**
Time	<.0001	0.0004	<.0001	<.0011
Fertilizer	0.0086	ns	ns	ns
Cultivar	0.0010	ns	ns	ns
Time*cultivar	ns	ns	ns	ns
Fertilizer*cultivar	ns	ns	ns	ns
Time*Fertilizer	ns	ns	ns	ns
Time*Fertilizer*cultivar	ns	ns	ns	ns

Table 3.23. Fertilizer main effects on seedling emergence in low salinity plot after 2 years in Ndoff, Senegal. For each parameter, values followed by the same letter are not significantly different ($\alpha = 0.05$).

	Emergence (%)
Control	76^{b}
Compost	76^{b}
Peanut Shell	87^{a}

Table 3.24. Year main effects on seedling emergence, plant height and the number of tillers in low salinity plot after 2 years in Ndoff, Senegal. For each parameter, values followed by the same letter are not significantly different (α = 0.05).

	Emergence (%)	Plant height (cm)	Total Tillers	Productive Tillers (%)
2014	71[b]	120 [b]	4[b]	42[a]
2015	89[a]	160 [a]	7[a]	23[b]

Table 3.25. Repeated measure ANOVA table of the effects of fertilizers, cultivars and time on plant responses in high salinity plot after harvest in 2014 and 2015 in Ndoff, Senegal.

	Emergence (%)	Plant height	Total Tillers	Productive Tillers (%)
Time	<.0001	ns	<.0001	<.0001
Fertilizer	0.0470	0.0015	ns	0.0079
Cultivar	ns	0.0182	ns	0.0198
Time*cultivar	ns	ns	ns	ns
Fertilizer*cultivar	ns	ns	ns	ns
Time*Fertilizer	0.0151	ns	ns	ns
Time*Fertilizer*cultivar	ns	ns	ns	ns

Table 3.26. Fertilizer*Year interaction effects on seedling emergence in high salinity plot after harvest in 2014 and 2015 in Ndoff, Senegal. For each parameter, values followed by the same letter are not significantly different (α = 0.05).

	Emergence (%)
2015, Compost	95[a]
2015, Control	92[a]
2015, Peanut Shell	92[a]
2014, Peanut Shell	87[ab]
2014, Control	63[bc]
2014, Compost	62[c]

Table 3.27. Fertilizer main effects on plant height and productive tillers in high salinity plot after harvest in 2014 and 2015 in Ndoff, Senegal. For each parameter, values followed by the same letter are not significantly different (α = 0.05).

	Plant height	Productive Tillers (%)
Control	95^{b}	21^{b}
Compost	123^{a}	37^{a}
Peanut Shell	140^{a}	39^{a}

Table 3.28. Year main effects on tillers in high salinity plot after harvest in 2014 and 2015 in Ndoff, Senegal. For each parameter, values followed by the same letter are not significantly different (α = 0.05).

	Total Tillers	**Productive Tillers (%)**
2014	3^{b}	48^{b}
2015	87^{a}	20^{a}

Tillers

Time main effects were significant on total tillers and productive tillers in both salinity plots. In addition to time, productive tillers were affected by amendment factor in high salinity. Pearl millet plant architecture is characterized by the development of tillers during the vegetative stage. Some of the tillers are productive, meaning they will ultimately produce panicles for grain production, other are not. However, the total number of tillers and productive tillers varies among cultivars. They also depend on soil properties.

Total tillers per hole were evaluated in 2014 and 2015 in low and high salinity plots. Total tillers increased from 4 in 2014 to 7 in 2015 in the low salinity site (Table 2.24), likely due to lower EC in 2015. By contrast, the productive tillers decreased from 2014 to 2015 in the low salinity site. In high salinity plot there were more productive tillers in compost and peanut shell-amended treatments (Table 3.27). The formation of axillary buds in the leaf axils and their outgrowth in responses to endogenous and environmental signals control tiller development. Given that bud outgrowth depends also on environmental conditions, the water and salt stress in 2014 probably led to a smaller number of tillers. The number of productive tillers is correlated to the panicle numbers.

Panicles Biomass and Grain Yield

In the low salinity plot, pearl millet cultivars had panicle length varying from 21.5 to 33 cm in 2014. Organic amendments had no effects on panicle production. Panicle length was different among cultivars, with SOSAT C88 having the shorter panicle (24.9 cm) in 2015. Given that plants were grazed by cows before harvest in 2014, panicle weight, total biomass and grain yield weights were not evaluated. There were significant differences among cultivars when comparing the length, diameter and weight of panicles in high salinity plot for 2015 (Tables 3.29 and 3.30). Overall, cultivar IBMV 8402 panicle length (17 cm) was smaller than Gawane (33 cm), and had smaller diameter (9 mm) than the one of SOSAT C88 (19 mm). These differences may have a morphological origin specific to each cultivar.

In 2015, neither plant biomass (mean = 4 kg ha^{-1}) nor grain yield (mean = 0.4 Mg ha^{-1}) were different among cultivars in low salinity site. With more rainfall in 2015, only the adverse conditions, particularly acidity, salinity and low nutrient content can explain the low yields. In high salinity site, plant responses were very low: 1.5 kg ha^{-1} of biomass and 0.1 Mg ha^{-1} of grain yield. Many reasons can explain this nearly null yield. Water may have been deficient, although the rainfall was judged satisfactory. Despite the large amount of water and the resulting salt depletion through leaching, the EC remained very high in high salinity plot (9 dS m^{-1}). As a result, water and nutrient uptake may have been limited by osmotic pressure, which affected plant growth, and ultimately plant yield.

Table 3.29. ANOVA table of the effects of fertilizers and cultivars on the productive phase in low and high salinity plots during 2015 growing season in Ndoff, Senegal. Note: 2014 data were not collected; plants were grazed by cattle.

	Panicle Length (cm)	Panicle Diameter (mm)	Panicle weight (kg ha^{-1})	Biomass (kg ha^{-1})	Yield (Mg ha^{-1})
Low salinity plot					
Fertilizer (P-value)	ns	ns	ns	ns	ns
Cultivars (P-value)	0.0017	ns	ns	ns	ns
Fertilizers*Cultivars (P-value)	ns	ns	ns	ns	ns
High salinity plot					
Fertilizers (P-value)	ns	ns	ns	ns	ns
Cultivars (P-value)	0.0448	0.0204	0.0106	ns	ns
Fertilizers*Cultivars (P-value)	ns	ns	ns	ns	ns

Table 3.30. Comparison of three pearl millet cultivar responses in low and high salinity plots during 2015 growing season in Ndoff, Senegal.

	Panicle Length (cm)	Panicle Diameter (mm)	Panicle weight (kg ha^{-1})	Biomass (kg ha^{-1})	Yield (Mg ha^{-1})
Low salinity plot					
GAWANE	36^{a}	10 ^{a}	0.33 ^{a}	4.0 ^{a}	0.36 ^{a}
IBMV8402	30^{ab}	11 ^{a}	0.38 ^{a}	3.9 ^{a}	0.40 ^{a}
SOSAT C88	23^{a}	14 ^{a}	0.49 ^{a}	4.5 ^{a}	0.42 ^{a}
High salinity plot					
GAWANE	33^{a}	15^{ab}	0.54^{a}	1.7 ^{a}	0.15 ^{a}
IBMV8402	17^{b}	09^{b}	0.19^{b}	1.5 ^{a}	0.09 ^{a}
SOSAT C88	20^{ab}	19^{a}	0.10^{b}	1.5 ^{a}	0.07 ^{a}

Conclusions

Three experiments were performed with seven pearl millet cultivars to assess their degree of tolerance to salinity. The first greenhouse experiment aimed to identify the cultivars that were tolerant to salinity. Performed in a loamy sand, the study revealed that two cultivars, Sosat C88 and IBMV 8402, had the greatest rates of emergence and the highest dry matter production. In the second greenhouse experiment, phosphogypsum increased the EC by adding soluble salts and decreased pH due to the low pH of the P byproduct. As a result, dry biomass was negatively affected by phosphogypsum. The high EC resulting from PG limited root growth. This may have been due to the use of plastic lined pots, which prevented salt leaching. Leaching would likely occur in the field in sandy and well-drained soil such as saline acid soils in Ndoff, especially when rainfall was high such as in 2015. From the seven cultivars, three were cultivated in saline acid sulfate soils in Senegal (sandy soils). Peanut shell and compost positively affect plant height in the high salinity plot. The rate of peanut shells and compost (10 Mg ha^{-1}) applied during the two years were very low, as revealed by calculations based on the laboratory analyses. Also the quality of the compost and peanut shells through composting need to be improved if we want these fertilizers to be more effective (i.e., for supply of nutrients, and raising pH and CEC, and improving physical properties). Overall (i) cultivars SOSAT C88 and IBMV 8402 performed best in saline greenhouse media; (ii) the fertilizers that elicited the best millet plant responses in the greenhouse experiment were PWC, PSS66 and NPK; (iii) phosphogypsum exacerbated the salinity effect by increasing growth media electrical conductivity; (iv) rainfall was more important on EC than treatments; (v) our results suggested that cultivars IBMV 8402 and SOSAT C88 be cultivated in saline soils amended with peanut shells.

3.5. Literature Cited

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