Soil Management for Improved Rice Production in Casamance, Senegal

Thioro Fall

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John Galbraith, co-Chair

Thomas Thompson, co-Chair

Wade Thomason, member

Ozzie Abaye, member

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Blacksburg, Virginia

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ABSTRACT

Rice is a staple crop for many countries, and is one of the top three food crops in the world. Environmental stresses such as drought, salinity, diseases, acidity and iron toxicity are likely to limit its growth and yield. In southern Senegal (Casamance), rice is mainly cultivated in lowland areas near mangrove swamps where salinity, acidity, and infertility constitute the main yield limiting factors. In the Casamance region, average rice yield is 1 to 2 t ha^{-1}. Our objectives were to 1) evaluate soil profile physical and chemical characteristics and monitor groundwater height, EC and pH throughout the rice growing season; 2) evaluate effects of two planting methods on salinity and rice yield, and 3) evaluate the response of soil properties and rice yield to addition of two locally available amendments—biochar and crushed oyster shell. Field experiments were conducted during 2014 and 2015 near Ziguinchor in southern Senegal, with the salt-tolerant cultivar WAR1. The site has a saline-sodic and acidic acid-sulfate soil. Two planting methods (flat and bedded) and three amendments treatments (18 t ha^{-1} biochar, 8.2 t ha^{-1} crushed oyster shell, and a combination of biochar+shell) with six replicates were tested in a split-plot design for their effect on rice yield and phenology and soil properties. All plots were fertilized. Plant tissue was collected at panicle differentiation for elemental analysis. We also measured water table height, EC, and pH weekly during 2014. A complete soil profile description and analysis was conducted. The water table was above the surface and very saline (>10 dS m^{-1}) during the first half of the growing season in 2014, but began to decrease at panicle initiation, reaching <4 dS m^{-1} by harvest. Planting methods and amendments did not have a significant effect on yield in 2014. However, yield was significantly higher in the biochar treatment compared to the control in 2015. Overall, yields were higher in 2014 than 2015. In 2014, soil salinity (EC) and sodicity (SAR) decreased to <4 dS m^{-1} and <13, respectively, in the flat treatment after harvest, but were significantly higher in bedded treatments. Soil pH increased from 4.4 to 7.7 in flat treatment where biochar+shell was applied. Rice yield was 3.51 t ha^{-1} in 2014 and varied between 2.44 to 3.18 t ha^{-1} in 2015 compared to 1 - 2 t ha^{-1} average yields in Ziguinchor. Our results show that rice should be planted flat (without raised beds) in lowland rice production systems in Senegal. Biochar shows promise for increasing rice yield.

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GENERAL AUDIENCE ABSTRACT

Rice is a staple crop for many countries around the world, and is one of the top three food sources globally. Many environments where rice is grown contain stressors likely to limit its growth and yield. In southern Senegal (Casamance region), rice is mainly cultivated in lowlands near estuaries where drought, salinity, acidity, poor soil fertility, and iron toxicity are the main limiting factors. In Casamance, average rice yield for local farmers is 1 to 2 tons per hectare (809 to 1618 pounds per acre), compared to worldwide average yield of more than 4 tons per hectare. The soil where our 2-year experiment (2014 and 2015) was conducted is highly saline-sodic and acidic, and the salt tolerant cultivar we grew yielded 3.4 tons per hectare in 2013. Our main objective was to increase rice yield. The water table height, salinity, and pH were measured weekly during the rice growing season, and the soil was described, sampled, and analyzed to better understand the water and soil resources. Two planting methods were tested: flat planting and planting on beds. Two soil amendments were compared with each planting method: biochar and crushed oyster shells, alone and in combination. An untreated control was included in the experiment. All plots were fertilized. Treatment effects on soil properties and yield were compared in a split-plot design. Plant tissue was sampled for elemental content. The water table was above the surface and was saline during half of the growing season in 2014, and decreased after rice grain head emerged. Planting methods and amendments did not have an effect on yield in 2014, but biochar amendment increased yield in 2015. In 2014, soil salinity and sodium decreased to below toxic levels late in the growing season in the flat plots but not in the bedded plots. Therefore, flat planting is more appropriate in these lowland rice production systems. Soil pH increased from 4.4 to 7.7 in flat planting where biochar+shell was applied. Soil available nutrients such as P, Mn, and Zn were significantly higher in flat planting compared to beds. Toxic levels of Na (> 2000 milligrams per kilogram) were measured in leaves sampled just before flowering. We recommend flat planting and amending soil with biochar in saline-sodic acid-sulfate paddy soils in Casamance to improve rice yield.

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Chapter 1: Introduction

Rice is the most consumed cereal in Senegal. It is mainly produced in the Northern region (Saint-Louis, Matam) in irrigated systems, and in the Southern region (Casamance) in rainfed lowland and upland ecosystems. The increasing population in Senegal from 3 million in 1960 to 14 million in 2014 (World-Bank 2016) necessitates more food and land to meet demand. From 1960 to 2015, rice consumption in Senegal increased from 163 (1000 t) to 1,500 (1000 t), and production increased from 53 (1000 t) to 480 (1000 t). Rice imports increased from 110 (1000 t) in 1960 to 1000 (1000 t) in 2015 (IndexMundi 2016). Food security and self-sufficiency rely on cereal supplies in Senegal but rice production encounters increasing challenges such land degradation, water scarcity, and rural poverty. In the Southern part of Senegal (Casamance), where this study was conducted, salinity, sodicity and acidity as well as low soil organic matter and poor fertility of the soils constitute the main limiting factors for rice production.

The Government of Senegal has implemented projects with a goal to reduce rice imports by producing more grain. However, these efforts have been unsuccessful. For example, in 2013 the PSE (Senegal Emerging Program) was initiated with PRACAS (Accelerated Program for Agriculture in Senegal) as one of its components. The objective of PRACAS is to ensure rice self-sufficiency by 2017. With a budget of 64 million USD to provide seeds, fertilizer inputs, and machinery, 38 million USD were allocated to the production of 600,000 t of paddy rice in the Northern part of Senegal while 26 million USD were invested in the Southern region to produce 400,000 t of paddy rice in rainfed lowland and upland ecosystems (USDA 2015). Despite those efforts, Senegal remains the second largest rice importer in West Africa after Nigeria (IndexMundi 2016).

In Casamance, rice production in mangrove swamps is mainly practiced by the “Jola” community. Rice is their dominant subsistence crop (Linares 2002). It represents a valuable tradition because some rituals are done only with the rice they cultivate themselves. Across different ecosystems, the Jola have developed techniques such as diking to control tidal waters as well as rainwater storage and distribution. Land management consists of incorporation of animal waste and plant residues as compost during the dry season and tillage after the first rain drops. Mineral fertilizer is not applied to rice paddies due to their high cost. During the last decade, average rainfall in Casamance has attained > 1200 mm nearly as much as before the 1970s drought in the Sahel (Blesgraaf et al. 2006). It had dropped from 1,500 mm to 1,000 mm and the rainy season lasted 3 instead of 5 months (Cormier-Salem 1999). As a consequence, the Casamance River became hypersaline and seawater intrusion begun to invade inlands (Savenije and Pagès 1992). Hence, rice cultivation in lowland mangrove was abandoned by the Jola due to high salinity and acidity (PERACOD 2008). Harvested rice could no longer last until the next growing season and imported rice became a vital food source for the Jola. Beside yield reduction due to salinity, migrate of the Jola to big cities was another consequence of land salinization. As a result, Jola families have seen their labors reduced and buying imported rice was the cheapest alternative since land preparation and harvest are done manually and require heavy labor. The drying of rice fields drives oxidation of iron sulfides, thus lowering soil pH to critical level for rice production. The model scenarios studied by Blesgraaf et al. (2006) show that the hypersalinity of the Casamance River is irreversible. The impact of salinity and acidity on rice yield in Senegal and West Africa in general, have prompted Africa Rice to test new rice varieties tolerant to environment stresses.

Given these major concerns at national and local levels, improved field management practices for acidic, salt-affected soils have become crucial. This research aims to identify management practices for increasing rice yield (WAR 1 salt tolerant cultivar) to 6 t ha^{-1} versus 3.4 t ha^{-1} in 2013. It also constitutes a basis for future research and planning for successful rice production in Casamance. The objectives were to (1) evaluate soil profile physical and biochemical characteristics and monitor groundwater height, EC and pH throughout the rice growing season, (2) evaluate effects of two planting methods on salinity, (3) improve soil chemical properties and increase rice yield by addition of two amendments—biochar and crushed oyster shell as a liming material.

Chapter 2: Literature Review

2.1. Lowland Rice Production: Potential and Constraints in Sub-Saharan Africa

Rice is a semi-aquatic annual grass, a short-day summer crop grown under diverse climatic and edaphic conditions. Rice belongs to the genus *Oryza* which contains about 22 species (Vaughan 1994). Among them, two species (*Oryza sativa* and *Oryza glaberrima*) are cultivated and 20 are wild. *O. sativa* is cultivated worldwide whereas *O. glaberrima* is grown in West and Central Africa (OECD 1999; Sanchez et al. 2013). Rice is photoperiod sensitive, meaning that its growth is affected by day length. This sensitivity increases with plant age up to 28 days then decreases as plants mature (Vergara and Chang 1985). Rice life cycle can be divided into three agronomic growth stages. The vegetative stage is from germination to panicle initiation, the reproduction stage from panicle initiation to flowering, and the ripening stage from flowering to full grain development (Moldenhauer 2001; Vergara and Chang 1985). The reproductive and ripening phases are more constant and stable than the vegetative phase, which takes longer. The optimum soil pH range for rice is 4.9 to 6.5 (Brady and Weil 2008).

Rice is a staple crop for many countries around the world. In 2014, paddy rice production worldwide was estimated at about 740 M tons from about 163 M hectares of harvested area (FOASTAT 2016). The contribution of Asia was ~ 90 % of production, America 5.1 %, Africa 4.2 %, and Oceania 0.5 % etc. China (mainland) and India accounted for 49% of Asian production. North African countries contributed 47 % of African production with 162,449 ha of harvested areas whereas Western Africa produced 34 % with 460,913 ha harvested, about 3 times that of North Africa (FOASTAT 2016). In Africa, Sub-Saharan Africa (SSA) particularly, land degradation, poor soil fertility management, low farm inputs etc. are the major causes of low rice yield. Average rice yield in Africa was 1.87 t ha^{-1} in 2000-2003, compared to the world average of 3.84 t ha^{-1} (Norman and Kebe 2006). In 2014, annual population growth reached 2.7 % in SSA compared to 2.5 in 2010 (World-Bank 2016). The increasing population across Africa results in the need for intensification of crop production. This situation incentivizes farmers in SSA to grow crops successively, depleting soil nutrients and therefore lowering their fertility. As a result, less fertile soils such as forest and grassland areas are converted to agricultural lands (Henao and Baanante 2006), and without fertilizer application. In addition to nutrient mining, the occurrence of drought, salt-affected soils, acidified soils, and low OM inputs constitute an obstacle to achieve food security and reduce rice importation in Africa.

During the past decade, the potential of SSA to successfully and economically produce rice to meet local demand has been investigated. Hence, critical decisions need to be made about options relating to sustainable agricultural expansion to cope with demand, poverty, land degradation and water scarcity. In Western Africa, rice is cultivated in variety of ecosystems classified as irrigated, rainfed-lowland, rainfed-upland, mangrove swamp and deep-water systems (Somado et al. 2008). Lowland rice ecology represents 20 – 50 M ha in West Africa, and a yield of 3 t ha^{-1} on average in only 2 M ha can reduce West African rice imports (Rice-LRVI 2006). According to (Bouman et al. 2007): “Rice production under flooded conditions is highly sustainable.” However, increasing threat of salinity associated with climate change (CC) consequences is an issue for rice production. Climate change also worsens drought, submergence and heat stresses on rice plants (Wassmann et al. 2009).

In West Africa, particularly in Casamance/Senegal, salinity, acidity, poor soil fertility and low organic C content in soils restrict the yield of lowland rainfed rice to about 1.0 to 2.0 t ha^{-1} (Wolfe et al. 2009). As a result, salt-tolerant rice varieties were developed by Africa Rice to improve yield. In Senegal, 45 rice varieties are cultivated (ISRA 2012) across the country. Among them are 26 varieties are for irrigated upland culture, 8 varieties for rainfed lowland, 7 varieties for rainfed upland and 4 varieties for mangrove. The latter group belongs to the salt-tolerant varieties (*Oryza sativa* L.) which are Rok 5, WAR 1, WAR 77-3-2-2 and WAR 81-2-1-3-2. In Djibelor, WAR 1 performs better in salt-affected soils. This cultivar was obtained from the crossing of IR 4595-4-1-5 / Pa Fant 213. Its life cycle is 135 days, and height 160 cm (ISRA 2012). Improved varieties require high fertilizer inputs to support plant growth in stressed environments. From an economic standpoint, however, rice should be produced at low cost to benefit farmers and consumers because 43 % of the population in Sub-Saharan Africa lived below the poverty line in 2012 compared to 56 % in 1990 (Beegle et al. 2016).

2.2. Hydrology and Geochemistry of Lowland Areas in Casamance

The hydrographic network of the Casamance region as well as its geochemistry are influenced by the ocean, estuary and river system. An estuary presents the characteristics of an ocean (sediment transport, saline water) and those of a river (sediment transport, fresh water), resulting in the creation of brackish water (Blesgraaf et al. 2006; Savenije and Pagès 1992). As a result, its hydraulic system is controlled by tides, fresh water discharge, and evaporation; and the deposition of sediments from the seaside is higher than that from the river. The Casamance estuary presents multiple stream branches which irrigate parts of the inlands. According to Blesgraaf et al. (2006), the lower part of the Casamance estuary is dominated by tidal floodplains with mangrove as the principal vegetation. As for the estuary, mangrove sedimentary and geomorphic characteristics in the Casamance, Sine-Saloum and Gambia rivers are mainly due to tidal current rather than fresh water discharge from the rivers (Marius 1982). These mangrove areas are subject to the semi-diurnal tide which governs the West African Coast. The geology of the Casamance estuary by Kalck (1978) cited by (Marius 1982; Marius and Lucas 1991) showed the presence of sandstone as the continental bedrock which appears under unconsolidated mud clays and sands at about 20 meters deep in mangrove areas. In these areas, the sediments consists of fluvio-marine deposits. They are dominated by quartz, clay, halite, and pyrite (Marius 1985). The clay fraction is composed of smectite from marine deposit and kaolinite from the upland sandstone. In addition, they present shallow soil profile, shallow groundwater table (50 cm), potential acid sulfate soil formation, and frequent inundation from saline tides (Cormier-Salem 1999; Marius 1982). Therefore, rice cultivation, the main agricultural activity in lowland mangrove areas of the West African Coast, is exposed to salinity and acidity problems as well as fresh water scarcity. Since marine deposits are predominant, the presence of Na and Cl ions as well as sulfates (SO_4^{2-}) from the sea determine the process of salinization and acidification of lowland rice fields. Marius (1982) reported that potential acid sulfate material to be present within 40 cm of the soil surface. Potential acid sulfate soils are usually poorly drained, highly pyritic, and their pH is nearly neutral or slightly acidic (Van Breemen 1982). The heavy clay layer contains 5% total S whereas the sandy mud has 2%. In submerged conditions, sulfate (SO_4^{2-}) is reduced to sulfide and the soil becomes less acidic, but the pH drops to about 2.0-3.8 when the field is drained and sulfides (S^{2-}) are oxidized to sulfuric acid.

2.3. Salt-affected Soils in Agricultural Lands

Origins of salt-affected soils

Salt-affected soils are those where soluble salts have accumulated to a concentration that affects soil physical, chemical, and biological properties as well as soil fertility (Rengasamy 2006; Szabolcs 1989). Salinization is primarily a natural (geochemical) process which occurs in almost all continents, but its result is more pronounced in arid and semi-arid regions where evaporation exceeds precipitation. The salts or ions responsible for the formation of salt-affected soils are mostly the cations Na^+, Ca^{2+}, Mg^{2+}, and K^+ , the anions Cl^-, SO_4^{2-}, and carbonates, bicarbonates and nitrates (Horneck et al. 2007; Richard 1954). Nearly all these cations are in higher concentration in rocks compared to soils with a ratio of 3:1 for Ca^{2+}, > 3:1 for Mg^{2+} and Na^+, and 2:1 for K^+ (Szabolcs 1989). This is due to the sequence of ion extraction from the minerals during weathering processes that occur in the earth's crust (Fersman, 1934 cited by (Szabolcs 1989). The higher the sequence level of ion extraction (I, II, and III), the lower the mobility of chemical elements during weathering processes. Sodium, Ca, Mg and K belong to the second sequence whereas Cl^- and SO_4^{2-} appear in the first one. Beside primary salinization, anthropogenic factors, wind-transported materials, sea water intrusion and rising water tables induce salt buildup in soil or secondary salinization. Human activities include use of poor quality irrigation water, and application of fertilizers and soil amendments (Rengasamy 2010).

Primary salinization occurs in more than 955 M ha worldwide whereas 77 M ha of salt-affected soils are due to human activities (Metternicht and Zinck (2003). Globally, 75 countries have large areas of salt-affected soils (Amini et al. (2015), but their distribution has not been fully mapped. (Massoud 1976) reported that 765 ha of land in Senegal are affected by saline.

In the Casamance, sea water intrusion and rising water tables are the major causes of soil salinity. Studies from 1987 to 1994 showed that the Casamance estuary has become hypersaline since the recurrent Sahelian drought in the late 1970's. According to (Savenije and Pagès 1992), an estuary is hypersaline when the net downstream salinity flux is not sufficient to evacuate salt accumulation due to evaporation. Decreased rainfall from 1,600 mm in 1935 to 1,100 mm in 1980 has induced a deficient water budget (Debenay et al. 1994). During, the last decade, average rainfall in Casamance has attained > 1200 mm, nearly as much as before 1970s drought in the Sahelian zone (Blesgraaf et al. 2006). Evaporation being constant, the amount of freshwater is no longer enough to evacuate brine and brackish water that accumulate during the dry season (Debenay et al. 1994). Salt-affected soils, whether due to primary or secondary salinization, are classified into two major groups: saline (high soluble salts), and sodic (high exchangeable sodium) with saline-sodic soils the intermediate. Salinity and sodicity are commonly assessed by the saturated paste extract to measure electrical conductivity (EC_e), sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP).

Characteristics of salt-affected soils

Salts are ionic compounds formed when an acid is neutralized by a base. They are electrolytes because they dissolve in water as free moving ions able to conduct electricity. The concentration of these electrolytes defines not only the morphology of the soil profile but also the fertility status of salt-affected soils (Szabolcs 1989). The main ions that contribute to salinity in soils are Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and rarely K^+ and NO_3^- (Bernstein 1975). All plants are sensitive to salts at a various concentrations depending on the species, development stage and the length they are exposed to salt stress. The principal effect of salts in crops is yield reduction. Under salt stress, many physiological and metabolic processes are altered by either increased osmotic pressure in soil solution (decreased water uptake by roots), or specific-ion effects (nutrient imbalance). Visual symptoms include retarded growth, stunted plants, dark green leaves, and sterile spikelets. (Abdullah et al. 2001; Bernstein 1975; Zeng and Shannon 2000).

Saline soils are dominated by high concentrations of soluble salts in the soil solution. They are characterized by an $EC_e > 4$ dS m^{-1}, SAR < 13 or ESP < 15, and a pH < 8.5 in the saturation extract (Brady and Weil 2008; Richard 1954). This soil condition reduces water potential in the rhizosphere, forcing plant root cells to lose water and further become dehydrated. Shoot growth reduction follows due to limited photosynthesis (Munns 2002a). Tillers and plant height are also impaired under osmotic stress (Hasanuzzaman et al. 2013). Beside stomatal closure, osmotic adjustment is a plant response to salinity but it requires energy (ATP production).

Sodic soils are monopolized by sodium ions on the cation exchange complex. They contain an $EC_e > 4$ dS m^{-1}, SAR > 13 or ESP > 15, and a pH > 8.5 in the saturation extract. They are considered as the most problematic of salt-affected soils due to the physical characteristic of the soils and their extremely high pH which disperses and/or dissolves soil organic matter (Brady and Weil 2008). For most plants, sodium is not an essential element, but for others it stimulates growth at low concentration. When plants accumulate toxic concentrations of Na^+ or Cl^- in leaves, photosynthesis is inhibited due to dehydration, turgor loss and death of leave cells and tissues (Flowers et al. 1991; Sudhir and Murthy 2004). Several studies reveal that ion effect causes nutrient disorder and deficiency.

Saline-sodic soils present both osmotic and ionic effects. They are characterized by an $EC_e > 4$ dS m^{-1}, SAR > 13 or ESP > 15, and a pH < 8.5 in the saturation extract. Their management is challenging due to a potential shift to sodic conditions if soluble salts are leached from the soil (Brady and Weil 2008). In Casamance, particularly in Djibelor, soils are characterized as saline-sodic. The average EC_e was 24.4 dS m^{-1}, SAR 30.2, and pH 4.4.

Impact of salt-affected soils on Rice Growth and Yield

In Casamance, rainfed lowland rice is grown over a span of five months. The growing season consists of three primary developmental stages: germination to panicle initiation, the reproduction stage from panicle initiation to flowering, and the ripening stage from flowering to full grain development. Nurseries are established Mid-July to August in upland to prevent potential drought and salt stress during germination. Young seedlings are then transplanted in lowland during mid-August after the rain has leached out part of the salts accumulated during the dry season. Thus, rice plants are subject to osmotic and/or specific-ion stress. Many studies have shown that rice is more sensitive to salt stress during seedling and grainfill stages than germination and vegetative (Carter 1982; Flowers and Yeo 1981). For example, Narale et al. (1969) showed that seed germination of *O. sativa* var. Dular was delayed at EC_e of 8.9 to 29.5 dS m^{-1} and completely inhibited at EC_e of 59.5 dS m^{-1} whereas vegetative growth and grain yield were restricted at EC_e 9.8 to 7.2 dS m^{-1}. Conversely, the study of Pearson and Bernstein (1959) revealed that salinity affected growth of ‘Caloro’ rice during tillering twice as much as during heading. Therefore, rice sensitivity to salt stress at any developmental stage varies between species and varieties. The final response of rice to salt stress is yield reduction. It results from the delay or absence of growth due to reduction of photosynthesis and vegetative growth, retardation and/or inhibition of panicle emergence, and increase in sterile floret or spikelet number. Straw weight may not be affected much but grain yield is still reduced at critical salinity level (Maas and Hoffman 1977). Yield reduction can also be due poor plant nutrition in saline-sodic conditions. Nutrient toxicity and deficiency occur often in sodic soils because of high Na uptake (toxic to some extent) to the detriment K, Ca, or Mg.

2.4. Acidity in Lowland Rice Paddies

Lowland mangrove areas are valuable agricultural lands for rice production due to their landscape position, microclimate and water availability. However, they provide optimum conditions for sulfide formation (Bloomfield and Coulter 1973). Acid sulfate soils constitute the predominant acidic condition of lowland mangrove areas. According to USDA (1999), actual and potential acid sulfate soils are those containing a sulfuric horizon characterized by the presence of sulfidic materials. These materials refer to the oxidizable sulfur compounds such as pyrite (FeS_2), mostly present in brackish water sediments. Potential acid sulfate soils are usually poorly drained, highly pyritic, and their pH is nearly neutral or slightly acidic (Van Breemen 1982). Pyrite is formed from the reaction between elemental sulfide (S^0) and iron sulfide (FeS), both generated by different processes (Pyzik and Sommer 1981; Wada and Seisuwan 1986). According to (Wada and Seisuwan 1986), pyrite forms between the upper well oxidized and lower well reduced horizons in mangrove areas. The well oxidized part of the substrate provides the ferric compounds whereas hydrogen sulfide (H_2S) is confined in the reduced parts. In pore water sediments, the formation of H_2S is due to anaerobic respiration of bacteria which use sulfate (SO_4^{2-} from sea water) as electron acceptor. Elemental sulfide forms from either the oxidation of H_2S or the initial reaction between goethite and aqueous sulfide (Pyzik and Sommer 1981; Yao and Millero 1996). On the other hand, hydrogen sulfide (H_2S) reacts with metal ions such as iron (Fe^{3+}) to form iron sulfide (FeS). The end product of the reaction between S^0 and FeS is the formation of pyrite. In mangrove soils, the level of pyrite is determined by the type of vegetation present because microbial decomposition of organic matter accelerates its formation. Bloomfield and Coulter (1973) found that areas under *Rhizophora racemosa* (Red mangrove) developed more acidity upon drainage compared to those of *Avicennia africana* (Black mangrove) due to the difference in root morphology of the two species. In Djibelor, mangrove vegetation is dominated by Black mangrove, which are more tolerant to salinity. In submerged environments, the reduction of sulfate to sulfide and H^+ consumption during reduction of Fe^{3+} drive soil pH toward neutrality (Konsten et al. 1994; Ponnamperuma 1972). However, when the soil dries out or is excavated, pyrite is oxidized, lowering soil pH to 3.8 or lower (USDA 1999). In lowland rice fields, leaching and reduction of sulfate de-acidify the soils to some extent (Konsten et al. 1994).

Impact of Acidity on Rice Growth and Yield

Low soil pH impacts rice nutrient availability and creates Fe, Al and possibly Mn toxicities as well as P deficiency. In wetland rice areas, Fe toxicity is more likely than Al and Mn toxicities (Sahrawat 2005) due to Fe^{3+} reduction to Fe^{2+} and the relative increase of soil pH under submerged conditions (Konsten et al. 1994; Ponnamperuma 1972). In flooded soils, Fe toxicity is more prominent due to the reduction of Fe^{3+} to Fe^{2+} by heterotrophic bacteria which use the iron as electron acceptor (energy source). In reduced environments, Fe^{2+} and Mn^{2+} becomes more available for plant uptake. In youngest fully-emerged leaf blade of rice at panicle initiation, the concentration of Fe and Mn required for adequate rice growth is 74 - 192 mg kg^{-1} and 252 - 792 mg kg^{-1} respectively (HAIFA 2010). The dominance of Fe^{2+} in the root zone induces nutritional imbalance in plants because it prevents the uptake of other nutrients, their transport and utilization (Fageria 1990). Excessive amount of Fe^{2+} uptake becomes lethal to plant cells due to an elevated production of ROS, which occurs when Fe^{2+} in rice roots is being translocated to the leaves (Becker and Asch 2005). In West Africa, the lowland rice yield gap reaches 45% on average but can range from 10% to 100% (Audebert and Fofana 2009). Manganese toxicity in acid soil affects grain yield more than rice vegetative growth due to high sterility (HAIFA 2010). Another problem encountered in acid soils is the absorption of phosphorus to Fe and Al oxides which makes it unavailable for plants. Phosphorus plays a central role in plant metabolism (ATP, ADP production for energy transfer and storage) but is the second nutrient most likely to be deficient in soils after N. In acidic soils, P is bound to Fe and Al metal oxides to form iron and aluminum minerals and become unavailable. In youngest fully-emerged leaf blade of rice at panicle initiation, the concentration of P required for adequate rice growth is 0.18 % - 0.29 % (HAIFA 2010). Deficiency in P is manifested by stunted plants and delayed maturity. In rice plants, reduced tillering and small diameter stems are the major effects of P deficiency. The flooding of potential acid sulfate soils makes P more soluble and therefore available because sorption and release of P is determined by the oxidation and reduction status of the soil (Patrick and Khalid 1974; Ponnamperuma 1972). Phosphorus is released as Fe^{3+}-P compounds is converted as Fe^{2+}-P under anaerobic conditions (HAIFA 2010).

2.5. Management of acidic and saline-sodic Soils in Lowland Rice Paddies

According to Khan and Jan (2010), the management of salt-affected soils necessitates a combination of agronomic practices based on different aspects of the local environment such as chemical amendments, water quality, climate, and existing farm system. Salt-affected soils are usually characterized by low fertility caused by their impacts on soil biota and vegetation as well as soil physical structure. They contain low SOC due to low organic material inputs from vegetation and low decomposition rate of SOM (Setia et al. 2011a). In sodic soils, dispersion of soil aggregates facilitates SOC mineralization, hence its potential loss through leaching and erosion (Wong et al. 2010). Therefore, soil amendments in salt-affected soils should improve SOC content, nutrient retention through cation exchange, and maintain adequate soil pH to provide nutrient availability. In addition to soil amendments, rice production under saline-sodic conditions requires the adoption of adequate planting techniques, land preparation as well as sufficient Ca supply that reduce salt and Na accumulation in the rhizosphere. In Casamance, organic amendments are widely used compared to chemical fertilizers, and beds are mostly adopted in lowland rice fields compared to planting "on the flat". Rice fields are tilled with artisanal tools to facilitate the building of beds and the development of rice roots in soil.

Biochar and soil fertility

Lehmann and Joseph (2015) defined biochar as " The solid product of pyrolysis, designed to be used for environmental management." The International Biochar Initiative (IBI 2014) adapted the definition of biochar from Lehmann and Joseph (2015): "Biochar is a solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment. Biochar can be used for a range of applications as an agent for soil improvement, improved resource use efficiency, remediation and/or protection against particular environmental pollution and as an avenue for greenhouse gas (GHG) mitigation. In addition, to be recognized as biochar, the material has to pass a number of material property definitions that relate both to its value (e.g., H/C_{org} ratios relate to the degree of charring and therefore mineralization in soil) and its safety (e.g., heavy metal content)." Biochar is a carbon-rich by-product used to improve soil fertility, increase C sequestration and reduce GHG emission. It is obtained from slow pyrolysis of plant materials such as crop residues and wood, poultry litter, wastewater sludge, biosolids and more. (Chan et al. 2008; Chan and Xu 2009). High heating rate (T^o/min) destroys cell structures (melting of cell structure) while slow pyrolysis allows volatile C release without major morphological changes (Cetin et al. 2004). Studies on black carbon (BC) in Amazonian forests and biochars have shown that these carbon-rich compounds have long residence time, high cation exchange capacity, strong sorption ability, and may increase soil pH (Brookes et al. 2010; Chintala et al. 2014; Jeffery et al. 2011; Lehmann et al. 2011).

Depending on the source materials (softwood, hardwood, leaves etc.) biochars have different nutrient content, physical and chemical properties. However, they are mainly composed of recalcitrant C, labile C and ash (Lehmann et al. 2011). The C content in biochars form aromatic structures, rings of six C atoms linked together without O or H (Lehmann and Joseph 2009), which define their stability in soil (Nguyen et al. 2010). Long exposure of biochars in soils (incubation time) increases their CEC due to the formation of carboxylic functional groups during biotic and/or abiotic oxidation of their outer (surface) and inner core (Cheng et al. 2006) which then creates the formation of organo-mineral complexed organic matter (Glaser et al. 2001). Furthermore, additional surface charge densities are created on biochars when they adsorb organic matter on their surface (Liang et al. 2006). In contrast, surface area and pore size (sorption ability) may also decrease when adequate heating temperature during pyrolysis is not achieved, and/or pores are clogged with soil mineral particles. This aspect infers that biochar mixed with organic matter is more beneficial and effective to mitigate low soil CEC and fertility. The sorption ability of biochars is an important aspect in nutrient cycling and retention, the fate of toxins and heavy metals in soils. Thus, heating temperature (ºC) followed by heating rate (ºC min^{-1}) plays a key role in the formation of both surface area and the porosity of biochars (Downie et al. 2011).

In addition to these physical characteristics, biochar has the ability to increase soil pH mostly in acidic soils compared to calcareous soils depending on the source material. Biochar applications (mixture of enhanced solids reduction (ESR) sludge, clarifier sludge and waste wood chips at different percentages) in acidic soils have increased soil pH by up to 1.73 (Van Zwieten et al. 2010). Furthermore, application of corn stover biochar at rates of up to 156 t ha^{-1} in acidic soil showed increased soil pH, EC and CEC at all application rates and with increasing incubation time (Chintala et al. 2014). Soil fertility of Southeastern Coastal Plain soils was improved by pecan-shell based biochar (Novak et al. (2009). They found that the metal oxides (ash), formed during pyrolysis from the cations K, Ca, Si, and Mg present in the pecan shell interact with the hydrogen ions and monomeric Al in soil to change pH and exchangeable acidity. Therefore, the ash content in biochar presents a liming ability as shown by the studies of (Lehmann et al. 2011; Nguyen and Lehmann 2009; Novak et al. 2009).

Oyster shell as liming material

Reclamation of acidic soils is accomplished by application of liming materials. Oyster shell has 96 to 98% $CaCO_3$ equivalent (Hamestera et al. 2012; Lee et al. 2008). In saline-sodic soils, the application of $CaCO_3$ rich-products might help remove the excess Na^+ ions by replacing them in the soil exchange sites over time, but the use of gypsum $CaSO_4 \cdot 2H_2O$ (Eq. 1) and sulfuric acid is preferred due to high pH and poor soil structure these soils present (Bower 1958; Sadiq et al. 2007). The reaction of $CaSO_4$ with sodium in soil always forms Na_2SO_4 which easily leaches out of the soil. The alkaline nature of sodic soils does not require addition of lime. Gypsum does not raise soil pH but replace the sodium by calcium and therefore remediates sodicity.

$$NaCO_3 + CaSO_4 \rightarrow CaCO_3 + Na_2SO_3 \tag{1}$$

In acidic soils with saline-sodic conditions, the application of lime is beneficial for plant nutrition. In Djibelor/Casamance, the application of oyster shell is primarily to raise soil pH (Eq. 2). In addition, farmers generally cannot afford the cost of gypsum or lime. The liming effect of oyster shell is more prominent in fine sandy loam soils than silt or clay soils due to their buffering capacity. Using different oyster shell rates, Lee et al. (2008) found that a rate of 8.0 t ha^{-1} has increased pH from 5.6 to 6.6 in sandy loam soils.

$$CaCO_3 + H_2O + H^+ \underset{\leftarrow}{\overset{\rightarrow}{}} Ca^{2+} + H_2CO_3 + OH^- \tag{2}$$

Planting Methods

Many scientists have evaluated the efficacy of bedded versus flat treatment in cropping systems. However, most studies were conducted in non-saline and irrigated upland areas. The majority of these studies took place in Mexico, Asia, Australia, Pakistan etc. where rice and/or wheat are the main crops produced mostly in rotation system. Bedded treatment is adopted to improve soil structure and aeration, manage nutrient and water inputs, and reduce cost of tillage and land preparation for farmers. However, it is not recommended in soils with low pH, shallow water table, high salinity, and where weed population is maximal (Beecher et al. 2003). In most studies, rice compared to wheat shows yield decreases in permanent beds and performs better in flat treatment with or without tillage. In each study, yield decrease was affected by different properties of the beds. In Punjab/India for example, soil water tension of about 10 kPa at 10 cm depth in sandy loam loamy soils (Kukal et al. 2005b) and at 15 cm depth in sodic silt loam

(Sharma et al. 2002) reduces rice yield in permanent beds as soil water declines below saturation. This means that there is a minimum moisture requirement to maintain reasonable rice yield. Inversely, Kukal et al. (2005a) found that continuous flooding is not necessary for rice because it can support a soil tension of 15 to 20 kPa. The decrease in soil tension can be related to high percolation from the beds due to their shape and accelerated by the formation of cracking upon wetting and drying of the soil (mostly in clayey soils). These aspects of the bed prove its efficiency in reclaiming waterlogged land (Bakker et al. 2010) but lead to the questioning of its effectiveness in management of salt-affected soils. In field conditions, salt accumulation on surface of beds is due not only to salt movement toward the center of the bed but also high evapotranspiration on its surface. Roberts et al. (2008) found that in subsurface drip irrigation system salt accumulation was high (EC_e 11 dS m^1) on the top 3 cm of the bed surface but dropped to below for 4 dS m^1 and was constant to 1.05 m. During their second-year experiment, the high salt level was recorded at 25 cm depth due to rainfall which have leached salts. Thus, under no flooded soil, timing of irrigation water is necessary for seedling survival. Holland et al. (2007) investigated the relation between soil structure and solute transport under bed cropping and conventional cultivation in South-Western Victoria. In the laboratory, a solute transport experiment was done using KCl solution (0.02 M and a pulse concentration of 2 M) applied to the soil surface. The first concentration was applied -30 mm tension on pores < 1mm and the second one at -5 mm tension on pores < 6 mm diameter. The leached solution was collected and EC was measured. They found that after application of the second concentration, solute transport (drainage flux) was faster in beds compared to conventional cultivation due to higher porosity and surface area (the extend of porosity) of the beds. Fast percolation does not induce rapid salt dissolution, therefore its removal. Water transported in preferential flow has lower solute concentration compared to the bulk of the soil due to the rapid percolation which does not allow salts to dissolve then leach out of the soil (Scotter 1978).

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Chapter 3: Soil Management for Improved Rice Production in Casamance, Senegal

Thioro Fall; John Galbraith, Wade Thomason, Simeon Bassene, Thomas Thompson

Abstract

Rice is the most consumed cereal in Senegal. Rice producers encounter several challenges, particularly in rainfed lowland agroecosystems of southern Senegal (Casamance region). High consumption of rice and low yield (<2.0 t ha^{-1} in Casamance) result in Senegal importing most of its rice. Environmental stresses such as acidity, salinity, sodicity, low soil fertility and organic C are the major causes of low rice yields in Casamance. This 2-year experiment (2014 and 2015) was conducted in Casamance to assess field management practices to increase rice yield by addressing the main edaphic constraints to yield. The objectives were to 1) evaluate soil profile physical and biochemical characteristics and monitor groundwater height, EC and pH throughout the rice growing season, 2) evaluate effects of two planting methods on salinity, and 3) improve soil chemical properties and increase rice yield by addition of two amendments—biochar and crushed oyster shell as a liming material. The yield of 'WAR1' rice, its growth parameters, and leaf and grain analysis, and soil chemical properties were evaluated in a split-plot design. The treatments consisted of two planting methods (flat and bedded treatments), biochar (18 t ha^{-1}), shell (8.2 t ha^{-1}), biochar + shell, and an untreated control. Amendments were applied once before planting in 2014. The groundwater regime and its EC and pH were monitored during the rice growing season, Aug. to Dec. 2014. The height of the water in the monitoring well showed that the water table was above the soil surface during the entire growing season, and water EC values > 10 dS m^{-1} were common until panicle differentiation, when salinity began to decrease. Rice yield was not affected by any treatment in 2014, and the average yield was 4.29 t ha^{-1}. Yield was significantly affected by amendments in 2015, with yield of plots receiving biochar (3.18 t ha^{-1}) significantly higher than the control (2.44 t ha^{-1}). The observed yield reduction during 2015 may have resulted from 32% sterile spikelets, possibly because of salinity. Most plant nutrient concentrations, except Na in leaves and Fe in grains were within normal ranges. The reduction of soil EC was more pronounced in flat treatment and soil pH was higher in flat treatments where shell or biochar+shell were applied. Soil C was increased with biochar application. Our results show that management practices that minimize salinity stress are crucial for achieving acceptable rice yield in acid, saline-sodic lowland production systems.

Keywords: WAR 1 rice cultivar, planting methods, biochar, shell, salinity, acidity

3.1. Introduction

Increasing rice yield in lowland areas constitutes a promising option to increase production and thus decrease rice imports in West Africa. Lowland rice production represents about 20 M to 50 M ha in West Africa (Rice-LRVI 2006). In Senegal, rice is cultivated mainly in river valleys (St. Louis, Matam, and Tambacounda regions) with irrigation, and in southern Senegal (Casamance region) under rainfed lowland and upland conditions. Average rice yield in 2008 was 6.0 t ha^{-1} in irrigated production systems compared to 1.0 to 2.0 t ha^{-1} in rainfed systems in Senegal (Wolfe et al. 2009). Average annual rainfall in Casamance has recently been > 1200 mm, nearly as much as before 1970s drought in the Sahel (Blesgraaf et al. 2006). It had dropped from 1,500 mm to 1,000 mm and the rainy season lasted 3 instead of 5 months during the drought events in the 1970s (Cormier-Salem 1999). As a consequence, the Casamance River became hypersaline and seawater intrusion became a serious problem (Savenije and Pagès 1992). Irrigated rice represents 70% of the national production, with 30% from rainfed systems. Rainfed lowland rice experiences a great diversity of growing conditions. These systems can be characterized by their topography, the amount and duration of rainfall, the depth and duration of standing water, and soil type (Nguyen 2016).

In Casamance the principal rice yield limiting factors are salinity, sodicity, acidity, poor soil fertility, and low soil OC. In rice-growing areas in the Casamance River delta, seawater intrusion in this tidal river system is the main source of salts and sulfate which induce salinization and acidification of rice paddies (Marius and Lucas 1991). In Casamance, particularly Djibelor, soils are characterized as saline-sodic. The range of rice yield loss due to salinity is estimated between 30 % to 50 % worldwide (Eynard et al. 2005). This yield loss results from the delay or absence of growth due to reduction of photosynthesis (Abdullah et al. 2001; Munns 2002a), retardation and/or inhibition of panicle emergence, and increase in sterile floret or spikelet number (Narale et al. 1969). Straw weight may not be affected much but grain yield is still reduced at critical salinity level (Maas and Hoffman 1977). Yield reduction can also be due poor plant nutrition in saline-sodic conditions. Nutrient toxicity and deficiency occur often in sodic soils because of high Na uptake, which may reduce uptake of K, Ca, and Mg. Soil pH < 4 impacts rice nutrient availability and creates Fe, Al and possibly Mn toxicities as well as P deficiency. In wetland rice areas, iron toxicity is more likely than Al and Mn toxicities (Sahrawat 2005) due to Fe^{3+} reduction to Fe^{2+} which tends to raise soil pH to near neutrality under submerged conditions (Konsten et al. 1994; Ponnamperuma 1972). Excessive Fe^{2+} uptake becomes lethal to plant cells due to elevated production of ROS when Fe^{2+} is translocated to the leaves (Becker and Asch 2005). In West Africa, the lowland rice yield gap reaches 45 % on average but can range from 10 % to 100 % (Audebert and Fofana 2009). Soils in Casamance are well weathered and therefore low in nutrient and carbon content. Animal manure constitutes the main organic inputs (Linares 2002) but are not enough to compensate low nutrient and carbon of the soil and thus improve rice yield.

According to (Rice-LRVI 2006), an average yield of 3.0 t ha^{-1} from only 2 M ha of the West African lowland rice ecologies would reduce rice import. In Ziguinchor, 52,950 ha of rice paddies only yield 2.0 t ha^{-1} on average (Wolfe et al. 2009). There is an urgent need for research into ways to increase rice yield in these ecosystems. We conducted a two-year experiment near Djibelor Senegal with the following objectives: (1) to evaluate soil profile physical and biochemical characteristics and monitor groundwater height, EC and pH throughout the rice growing season; (2) evaluate effects of two planting methods on salinity and rice yield, and (3) evaluate the response of soil properties and rice yield to addition of two amendments—biochar and crushed oyster shell as a liming material.

3.2. Materials and Methods

Site Characteristics

The present study was conducted in the lower Casamance region of Senegal near Ziguinchor. The experimental field (in Djibelor) is located at 12º34’16.46’’ N, 16º18’32.43’’ W and corresponds to the lowland mangrove area influenced by semi-diurnal tide consisting of two high tides and two low tides during a period of 24 hours and 50 minutes (Blesgraaf et al. 2006). The amplitude of the tide reaches 1 m on average and salinity is maximum in June and minimum in October (Posner 1988). At Pointe of Diogue (mouth of the Casamance estuary), the tide amplitude varies between 1.5 and 1.6 m during spring tide and 0.4 to 0.5 m during neap tide (Blesgraaf et al. 2006). The distance between Pointe of Diogue and Djibelor is approximately 94.8 km. Djibelor is approximately 90 m from the mangrove forest and 2.93 km from the main channel of the Casamance River, which has become hypersaline since the 1970s drought events (Savenije and Pagès 1992). According to Posner (1988), the saline part of the Casamance River extend to 220 km upstream from the mouth and saline water rises as far as 130 km inland.

In Casamance, the area of mangrove in Ziguinchor and Bignona was estimated at 120,000 ha at the beginning of 1980, and 70,000 ha in 1993 when Ziguinchor accounted for 40,000 ha (PERACOD (2008). The vegetation is composed of *Rhizophora racemosa* (Red mangrove) and *Avicennia africana* (Black mangrove). The Union Mondial pour la Nation or UICN estimated 65,000 ha of mangrove in 2004 for the two regions (UICN 2016). According to PERACOD (2008) this decrease is due to salinization which has led to the destruction of mangrove forest in Casamance, and their intensive exploitation by the population who could no longer grow rice. In Djibelor, soils are fine sandy loam and black mangrove represents the dominant vegetation.

Prior to our experiment, a full soil profile description was done in the research field which corresponded to the nearest plot to the mangrove (90 m). We dug a hole to the depth of the groundwater (130 cm). Soil samples of the profile were taken by horizons and each one was described based on textural classes determined from the pipette method. The structure (grade, size, and shape) of the aggregates was estimated visually. The redoximorphic features (Fe and Mn concentrations, and depletions) were determined based on visual observations and using a Munsell soil color book. Soil chemical analysis was performed for each horizon.

Since 2009, rainfall has been recorded using a rain gauge at the Djibelor research center. The Casamance region, within the 1000 to 1200 mm yr^{-1} isohyet, is characterized by a monomodal rainfall regime with a single peak during the year. Annual rainfall exceeds 1200 mm. The rainiest months are July, August and September (Figure 1). Delayed rainfall in 2014 rainy season has limited the amount of precipitation in July to 66 mm compared to 413 mm in 2015 season. In 2014 growing season, heavy rainfall was recorded in August with 626.5 mm. Average rainfall in 2014 and 2015 was 1365 mm and 1442 mm respectively within a 73-day period during each season.

Piezometer installation

Nine sets of piezometers and 3 monitoring wells were installed around the experimental site to monitor the watertable and its properties (pH, EC and height) on a weekly basis. The locations were selected based on the distance to the mangrove area. Thus, the lower site was distant 90 cm form the mangrove, the middle site 333 cm, and the upper site 499 cm. Our study plots were located in the lower site. Shallow and deep piezometers (30 cm apart) were installed based on the method proposed by WRAP (2000) to provide information about groundwater recharge or discharge, as well as water quality. The depth of each piezometer varies based on the soil profile depth of the location they were installed. In our experiment plots, piezometers were placed at 45 cm (2Btng2 horizon) and 115 cm (3Cgz2 horizon). Piezometers were perforated PVC pipe at the bottom only and placed into the ground to collect water. They were sealed with bentonite above the perforated zone to prevent down flow of water. Thus, water did not come from the layer (s) above the zone of perforation but underneath it by pressure. Unlike piezometers, monitoring wells were perforated from below ground to the bottom of the pipe. They give the best estimate of water table height in soil because water does not enter in the well under pressure.

Experimental Design

In Senegal, 45 rice varieties are cultivated (ISRA 2012) across the country. Among them 26 varieties are for irrigated upland culture, 8 varieties for rainfed lowland, 7 varieties for rainfed upland and 4 varieties for mangrove. The latter group belongs to the salt-tolerant varieties (specie *Oryza sativa* L.) which are Rok 5, WAR 1, WAR 77-3-2-2 and WAR 81-2-1-3-2. In Djibelor, WAR 1 cultivar performs better in salt-affected soils based on ISRA unpublished results in 2013. This cultivar was obtained from the crossing of IR 4595-4-1-5 / Pa Fant 213. Its life cycle is 135 days, and height 160 cm.

The field was tilled (disked and harrowed) with a tractor prior to implementation of the experiment in 2014 and no tillage was performed in 2015. Soil properties, rice yield, and phenological parameters were evaluated in a split-plot design with six (6) replicates. Two planting methods and two soil amendments were tested. The experimental area for this study was divided into six blocks. The planting methods consisted of beds (R) with 20 cm height and flat (F) treatment randomly assigned to the main-plots which were each subdivided into four sub-plots where soil amendments were randomly applied. The sub-plot size was 1m width ×5m long. Those amendments included biochar at 18.0 t ha^{-1}, crushed oyster shell at 7.2 t ha^{-1}, biochar and shell in combination (18.0 t ha^{-1} of biochar + 7.2 t ha^{-1} of shell), and an untreated control. Biochar and shell were applied before planting only in 2014. In addition, all subplots received the same amount of NPK fertilizer as 15-15-15, 13-00-50, and urea during both seasons. The resulting NPK rates were 373 kg ha^{-1}, 110 kg ha^{-1}, and 134 kg ha^{-1} respectively. In both growing seasons, NPK fertilizer was applied at transplanting. The NPK rate was selected based on Arkansas recommendation for a target yield of 6 t ha^{-1} and also ensure that fertilizer will not be a limiting factor. Urea was split in two applications, one half 20 days after transplanting (start tillering) and the other 45 days after transplanting (panicle initiation). Rice was transplanted on August 22nd 2014 and August 19th 2015.

The wood biochar used in this experiment corresponded the residue of charcoal not qualified as high energy source (size and softness) by “Bois Energie du Senegal” (Wood Energy for Senegal). Standard production for charcoal is a slow pyrolysis of *Eucalyptus camaldulensis* principally in an Adam kiln at temperatures of 600^{o} and 750^{o} C for 26 to 30 hours. The biochar was passed through a 5 mm sieve for field application. The characterization of the biochar (Table 1) was performed based on Standards and Guidelines of the International Biochar Initiative (IBI 2014). The measured parameters were pH, EC in a 1:20 ratio, ash and moisture using ASTM (2013) method. Total mineral content was determined by strong acid digest method using MARS Xpress microwave. However, 8% acid concentration was obtained by adding 8 mL nitric acid (HNO_3) into vessels containing 0.5 g of biochar compared to the proposed method by (Rajkovich et al. 2011). Exchangeable cations and CEC were determined using (1M NH_4OAc) at pH 7. Rayment and Higginson (1992) method was used to determine available nitrate (NO_3^- -N) and ammonium (NH_4^+-N) using 2M KCl extraction. The CN ratio as for the soil was determined using the Elementar vario Max CN Analyzer. However, biochar was analyzed as soil containing > 40% C whereas the soil samples in this study were are analyzed as mineral with < 40% C in the vario Max.

Oyster shells were burned for about 10 min in open air using traditional methods. The heating temperature was not controlled and the goal was to burn the shells so that they were easy to crush with a mortar and pestle. The crushed shell was passed through a 1 mm sieve. The chemical analysis of the shell was based on the AOAC (1998) method for both effective $CaCO_3$ equivalent and lime equivalent (Table 2).

In 2014 and 2015 rice was transplanted (Aug. 22nd and Aug. 19th respectively) into plots at a density of 25 plants m^{-2}. The plants were 20 cm apart. Rice phenological properties on the dates of 50% panicle differentiation (Nov 3rd to 9th in 2014 and Nov. 5th in 2015) and 50 % anthesis (Nov 7th to 15th in 2014 and Nov. 10th in 2015) were measured. Tillers and panicles were counted on three random one-meter rows excluding border rows. Between the vegetative and reproductive stages, fifty (50) Y-leaves – most recent, and fully expanded leaves – were harvested in each subplot for nutrient analysis. Plant height was measured at two locations in each subplot, and rice grain yield and straw weight were obtained at harvest on Dec. 15th 2104 and Dec. 21st 2015. Plants in the border rows (edges) were removed before harvest, so were not included in the yield measurement. In our experiment, the intended harvested area was 3.83 m^2, which corresponded to the area occupied by 96 plants. At harvest, 50% of the plants died in the beds and 40% in the flat treatment, resulting in a high variability in yield. Due to the generally vigorous appearance of the surviving plants within the plot, we considered mortality to be a random rather than a treatment effect. Hence, yield was normalized by considering the harvested area for each subplot as the one occupied by the number of harvested plants (not the expected 3.83 m^2). The covariate (percent live plants) was accounted in the model to better explain yield response. The same method was applied in 2015 to measure yield. At harvest, 17 % of the plants died in the beds whereas 25 % were lost in the flat treatment. In addition, the percent of sterile spikelets was measured by randomly selecting three piles of 100 grains and counting the number of sterile grains.

Soil samples were collected within each subplot before amendment application in 2014 (initial) and after harvest in 2014 and 2015. We collected a composite of three random subsamples at 15 cm depth in each subplot. The samples were air-dried, ground, and sieved to <2 mm. Soil pH was measured in a 1:1 (vol:vol) soil to water ratio. Soil exchangeable nutrients (P, K, Ca, Mg, Fe, Mn, Zn and B) were extracted using Mehlich 1 solution and analyzed by ICP-AES (Mehlich 1953) after the samples were shaken for 5 min and filtered. The CN ratio and soil total C and total N were measured with an Elementar vario Max CN Analyzer. Each sample was ground for three minutes with a Retsch mortar grinder and sieved through an 80-mesh sieve (0.18 mm opening). The temperature in the combustion tube was 850^o to 1150 ^{o}C. Salinity (EC_e) and sodicity (SAR) were measured in a saturated paste extract (Richard 1954). The SAR was calculated after Richard (1954), and ESP was estimated from the SAR. In addition to the above soil analyses, the seven soil profile horizons were tested for CEC using 1M ammonium acetate (1M NH_4OAc) at pH 7 (Chapman 1965). Exchangeable aluminum (Al^{3+}) was determined in a 1N KCl extract (McLean (1965), and exchangeable acidity (H^+) was measured in a $BaCl_2$-TEA extract (Peech (1965). Particle size analysis was done using the pipette method (Gee and Bauder (1986). Plant tissue samples (leaves and grains) were ground using a Wiley mill with a 1 mm sieve. The samples were analyzed for nutrient analysis using nitric/HCl microwave digestion and ICP (Chen and Ma 1998). The nitrogen was measured with a LECO nitrogen analyzer (Kowalenko 2001).

Data Analysis

Data were subjected to statistical analysis following ANOVA and treatments were differentiated using Tukey’s HSD test $p = 0.05$. JMP software (SAS Institute Inc. Cary, NC, USA) was used to perform the analyses, and Minitab 17 (Minitab Inc. State College, PA, USA) was used for outlier diagnostics and regression analysis.

3.3. Results

Soil Profile Description and Hydrology

Soil profile characterization (Tables 3 and 4) shows the presence of three parent materials and seven horizons to 130 cm depth. The soil textural size classes for these horizons are fine sandy loam (FSL), sandy clay loam (SCL), and loamy fine sand (LFS) from the surface to 130 cm. The soil profile is saline-sodic and acid throughout. Gleying—due to oxidation-reduction of Fe--was evident throughout the profile below 22 cm depth. Carbon and N concentrations were highest in the Apnz1 horizon, due to decreasing amounts of organic matter with depth. Sodium and Mg concentrations were highest in the surface horizon and K concentrations were lowest with depth; otherwise available nutrient concentrations were relatively uniform within the profile. Sulfur concentrations were highest near the bottom of the profile, presumably reflecting the accumulation of Fe sulfides. During groundwater discharge, dissolved salts, reduced Fe, and sulfur are brought to the soil surface. During the dry season, evaporation exceeds precipitation and therefore salts are left behind. The supply of oxygen in aerated conditions induces the oxidation of iron to Fe^{3+} and sulfate is oxidized to sulfuric acid, lowering soil pH during the dry season.

Experimental Results for 2014

Water level

During 2014, the higher level of the water table in the shallow piezometers compared to the deep ones showed a net drop or downward flux of the water table (Figure 2) for all 3 locations. This trend was observed from the 2nd to 9th August 2014, a week after they were installed. During the same period, water height in the monitoring wells indicated that the water table was below soil surface. A week later, an upward flux was observed in both piezometers and wells, and lasted for the remainder of the growing season. In the lowland monitoring well, two peaks of water height were noticed on 23rd August and 7th October 2014 with respectively 44 cm and 36 cm above surface. The water level in the monitoring well confirmed that the field was submerged during almost the entire growing season (Figure 3).

Water EC and pH

The EC of the water in the piezometers was < 4.0 dS m^{-1} in upland (Figure 4) but increased toward the estuary to 10 dS m^{-1} to 14 dS m^{-1} in midland and lowland positions, respectively. By the end of the growing season, it dropped to < 4.0 dS m^{-1} in the midland and lowland on 13th and 27th October respectively. At the lowland position, where the experimental plots were located, water EC was >10 dS m^{-1} from transplanting until panicle initiation; then decreased steadily until harvest. Overall, EC was higher in deep piezometers, which indicates the influence of brackish river water. Cumulative rainfall from June to September 2014 was 1277 mm, with only 88 mm in October. Groundwater pH was > 4 at the 3 locations during the growing season (Figure 5), with no apparent trends due to landscape position.

Rice yield and yield components

Rice yield in 2014 was not affected by treatment main effects or interactions (Table 5), but was affected by percent live plants (the covariate). The average yield across treatments was 4.39 t ha^{-1}, much higher than the average for this area, despite highly saline conditions during the first part of the growing season. Tillers and panicles m^{-2} were significantly affected by planting method and amendments (Table 5). The number of tillers and panicles was higher in beds compared to flats. Between amendments, tillers and panicles were lower in the biochar+shell compared to other amendments (Table 6). As for yield, straw weight and plant height were not significantly affected by the treatments.

In 2015, rice yield was significantly affected by amendments and the covariate percent of live plant (Table 5). The highest yields were recorded in the biochar treatment at 3.18 t ha^{-1} which was significantly different from the control (Table 6). From 2014 to 2015, we observed a yield decrease in yield of 20 % in the treatments receiving shell, 32 % in treatments receiving biochar, and 39 % in treatments receiving biochar plus shell. Yield in the control treatments was 48% below that in 2014. There is no clear explanation for the yield decrease in 2015 compared to 2014. Unfortunately, EC was not measured in water in piezometers in 2015. In 2015, we noted 32% sterile spikelets, which may partly explain the decreased yield. The percent sterile spikelets was not statistically different among treatments. In 2015, plant height was significantly affected by the interaction between planting methods and amendments. In flat treatment where biochar+shell was applied, plant height was at its maximum (160 cm for the WAR 1 cultivar). Plant lowest heights were recorded on bedded treatment where biochar+shell and shell amendments were supplied.

Tissue nutrient analyses in 2014 (data not shown) revealed few significant differences in nutrient concentrations among treatments. Across all treatments, average leaf Na concentration was 3,560 mg kg^{-1}, compared with the toxic concentration of >2,000 mg kg^{-1} (SAAESD 2009). Leaf iron concentrations were also not significantly different among treatments, with an average concentration of 99 mg kg^{-1}. HAIFA (2010) reported that >192 mg Fe kg^{-1} are toxic to rice.

Soil pH, EC, SAR, and exchangeable nutrients

Soils in the lowland area are saline-sodic because of a pH < 4, an EC > 4 dS m^{-1}, and SAR >13 (Figure 6). Before any treatment application, soil pH, EC and SAR were 4.4, 24.4 dS m^{-1} and 30.2 respectively (Figure 6). The EC and SAR measured after harvest in 2014 were significantly affected by planting methods (Table 7) and were lower in the flat treatment compared to beds (Table 7). At harvest, the EC was 5.2 dS m^{-1} in the flat treatment compared to 14.6 dS m^{-1} in beds while the SAR was 10.6 in flats and 21.3 in beds (Table 8).

Soil pH and exchangeable Ca were significantly affected by the interaction of planting method and amendment (Table 7). The highest soil pH and exchangeable Ca were obtained in flat treatments with biochar plus shell. In addition, the biochar applied was rich in mineral elements and Ca principally (Table 3). The result of the shell analysis shows its $CaCO_3$ equivalent is 102 % but the effective $CaCO_3$ equivalent was 60.9% due to its finesse**.** Calcium is the dominant exchangeable cations in most soils. As a result, the highest CEC values were recorded in flat treatment where shell and biochar+shell were applied. Most soil nutrients (P, K, Mg, Mn, Z, B, and C) were significantly affected by main effects of planting method and/or amendments (Table 7). Potassium and Mg were higher in beds compared to flat treatments but the Mg: K ratio was not significantly different among planting methods. Given the ratios Ca: Mg (4.1) and Ca: K (13.4) in the flats, low K and Mg levels were due to potential leaching with the downward flux of the water table. The micronutrients Zn and Mn were higher in flat treatments compared to beds (Table 8). The availability of Zn and Mn was enhanced by soil pH in the flats at the exception of Mn which tends to be more available at low pH. Manganese was also affected by addition of amendments which as well had significant impact on P, B and C in soil. Manganese was higher in biochar+shell treatment compared to shell and control. Phosphorus and boron were higher in shell treatment which presents a mean difference with the control treatment. Although the biochar has low carbon content, soil C was significantly higher in biochar and biochar+shell amended plots**.**

3.4. Discussion

Soil profile description and hydrology

The lower site (study plots) is characterized by the existence salinity, sodicity, and acidity are the predominant conditions as shown in figure 6. The soil profile in this lower site was classified as Fine-loamy, kaolinitic, isohyperthermic family of Typic Kandiaqualfs (Figure 7). The soil has an argillic horizon between 22 and 55 cm. The soil contained high levels of salinity, being moderately to strongly saline throughout (Table 1 and 2). EC > 30 dS m^{-1} was found in the surface layer and the lower profile, with lowest values between 10 and 40 cm. Sodium levels are high, indicated by SAR > 27 throughout. Salinity is mainly caused by water intrusion and inundation from the estuary, as well as groundwater discharge which carried dissolved salts. The sandy texture of the soils allows dissolved soluble salts to infiltrate to deeper horizons following the rainy season. As the soil dries further, however, evaporation draws saline soil solution to the surface where the salt precipitates. After the start of the next rainy season, the rising groundwater builds in salinity as it rises through the soil profile during groundwater discharge. In the upland, the level of salinity is very low because the groundwater is diluted by rainfall. Soil pH is < 3.7 throughout, except in the layer between 55 and 79 cm where it is 4.9. The total sulfur is more than 0.2% in the three horizons below 55 cm, indicating the presence of sulfidic materials. The soil samples were not tested to see if the pH dropped rapidly upon oxidation, so the presence of a sulfuric horizon cannot be confirmed. However, the soil has very low pH (<2.7) and very high levels of Mehlich-1 extractable Fe in the lowest two horizons, in a deposit that is sandier and different parent material than the horizons above. It is unclear how deep the water table drops and allows oxidation. Water from the estuary is a source of sulfides that may later oxidize into sulfates, increasing acidity and making even more Fe soluble.

Precipitation controls the dynamics of groundwater levels (Figures 1 and 3). In Djibelor, the amount of rainfall during the 2014 rainy season increased water table level in the piezometers as well as monitoring wells to above the soil surface during almost the entire rice growing season (Figure 2). However, fresh water discharge was not sufficient to dilute salinity in groundwater for the first two months of the growing season (Figure 4). In the Cgz horizon, the EC was 55.3 and 62.4 dS m^{-1} in the lower site. When the groundwater rises under pressure, it dissolves salts contained in lower horizons and increases water salinity. By the end of the rainy season (October), salinity in both shallow and deep piezometers dropped to < 4.0 dS m^{-1} , similar to the salinity level of the tide in October (Posner 1988). The pH of the groundwater in the piezometers was near neutrality even though the acidity in the deep horizons was extremely low.

Rice yield and yield components in 2014

In 2014, there was no treatment effect on rice yield. For more than two weeks after transplanting in 22 August 2014, seedlings died, resulting in a reduction of the number of plants by 50 % in the bed versus 40 % in flat treatments. The height of the water table (Figure 4) and water EC values confirm that rice was transplanted in saline conditions and therefore seedlings were exposed to osmotic stress during transplanting when rice plants were translocated from a non-saline nursery to a saline-sodic soil. The reduction of seedling density was observed during the first half of the growing season (Figure 5). Osmotic stress is due to a high concentration of soluble salts in the soil solution and induces seedling wilting and death (Läuchli and Grattan 2007). At panicle differentiation, Na concentration in leaves was 3,560 mg kg^{-1}, and was above the critical level (> 2000 mg kg^{-1}) for Na injury in rice leaves (SAAESD 2009). Some salt-tolerant varieties tend to concentrate Na or Cl in old leaves to prevent their potential toxicity (build-up in cytoplasm or cell wall) by compartmentalizing them in the vacuoles (Eynard et al. 2005; Munns 2002a). Toxic level of Na in leaves causes chlorosis and death (Läuchli and Grattan 2007), inhibits photosynthesis due to dehydration, turgor loss and death of leave cells and tissues (Flowers et al. 1991; Sudhir and Murthy 2004). As a consequence, photosynthesis is reduced at the whole plant level impacting yield and yield components. Seedling reduction and high Na concentration in leave did not impact average rice yield of 3.51 t ha^{-1} compared to the average rice yield as reported by Wolfe et al. (2009) for Ziguinchor region (1 to 2 t ha^{-1}).

Soil pH, EC, SAR, and exchangeable nutrients

The flat treatment was more favorable to salt leaching or dilution of salts than the bedded treatment, as shown by the lower EC and SAR in soil samples collected after harvest (Tables 7 and 8). The decrease in soluble salt concentration after harvest was likely due to the fact that salt leaching was more likely in the flat treatments, compared to the bedded treatment. In addition, the effect of tillage in salt redistribution in the soil was very important. After tillage, the average Na concentration in the top 15 cm was one-fourth that in the top 10 cm before tillage. As mentioned by Bakker et al. (2010), the shape of the beds does not allow effective leaching of salts. Evaporation and resulting precipitation of salts results in more salt retention in beds as the paddy dries. In the flat treatments, better infiltration of water induced leaching of excess salts when the water table dropped. Neither he main effect of amendments nor the interaction of planting methods and amendments had significant effects on soil salinity. However, Chintala et al. (2014) found that biochar from corn stover and switchgrass, and lime applied at different rates increased soil EC compared to the control. The increase of soil EC followed by biochar application was due to its ash content which is primarily composed of mineral nutrients or salts. In acid-sulfate, saline-sodic soils, the application of lime or equivalent results in the formation of gypsum (Sylla 1994). Given the total sulfur content in the soil surface, if any gypsum has been formed, it may have reacted with sodium carbonate to produce readily leachable sodium sulfite anion, thus reducing content of Na ions in soil surface in the flat treatment.

The addition of liming materials in flat treatments increased exchangeable soil Ca and pH. Brookes et al. (2010) found that Mycanthus biochar processed at 700^o C increased soil pH from 4 to more than 5 compared to that at 350^o C (4.0 to 4.5). Biochar has the ability to hold nutrients through its sorption property and therefore improve soil CEC. In addition, the biochar source used in this experiment is rich in mineral nutrients such as Ca, K, and Mg. The ability of biochar to increase soil pH reside in its ash content which is determined by the temperature at which biochar was produced. In addition, the char may present the alkalinity effect of the source material. For example, Yuan and Xu (2011) tested the liming ability of nine biochar sources composed of legume and non-legume materials. They found that the liming effect of legumes based biochar to be greater than that of non-legumes and attributed these differences to the accumulation of more alkali in legume plants. Using different biochar sources at 3 pyrolysis temperatures, Lehmann et al. (2011); Nguyen and Lehmann (2009); Nguyen et al. (2010) found that the higher the temperature, the higher the ash content and therefore the higher the pH. As a result, biochar liming ability increases as its pH gets higher. Van Zwieten et al. (2010) obtained increase in soil pH at 2 units biochars with 30 % $CaCO_3$. Yuan and Xu (2011) found a correlation of 0.95 between soil pH and biochar alkalinity.

The increase in soil pH in flat treatments has resulted to a higher availability of nutrients such as Mn, and Zn whereas K and Mg was higher in beds. Likewise, nutrient concentration in plant tissues (P, Zn, and Mn) was more pronounced in flats. Shell and biochar+shell application has improved P and B availability whereas biochar increased soil C. Biochar plays both the role of nutrient addition and retention (Lehmann et al. 2003). The application of Ca-rich material has improved soil pH and therefore nutrient availability.

Rice yield and yield components in 2015

In 2015, the effect of soil amendments has significantly affected yield. However, yield has decreased by 35% compared to 2014. We measured 32% sterile spikelets. Yield components such as panicle number and length and grain fertility are the major factors that reduce rice yield with more than 50 Mm NaCl in soil solution (Shereen et al. 2005). High salt concentration can induce up to 77 % yield reduction, depending on the cultivar. Ologundudu et al. (2014) found a decrease in root (20 % to 100 %) and shoot dry weight (13 % to 90 %) with increasing salinity level from 0 to 15 dS m^{-1}. In our study, tillers and panicles m^{-2} were higher in beds in 2015 compared to flats in 2014 statistically. The more tillers in beds can be due to lower plant density when rice plants were lost after transplanting resulting in less competition for nutrients and light. The biochar+shell amendment had the lowest tillers and panicles in both years. In 2014, rice plants did not suffer from nutritional disorder. Despite the excessive sodium content in leaves and Fe content in grains, the most essential nutrients were in adequate ranges in leave tissues.

Summary and Conclusions

In the Casamance region of southern Senegal, lowland rice is cultivated in highly saline conditions near the tidal Casamance river. Groundwater is saline and during the early part of the growing season, dominates the water balance of rice paddies near the river. As the rainy season increases in intensity, salinity may decrease as rainwater dominates the water balance. Avoiding salt stress is one key to successful rice production in these systems. We conducted field experiments during two seasons near Djibelor in southern Senegal to evaluate the effects of planting method and soil amendments on rice yield. In 2014, water salinity was >10 dS m^{-1} from transplanting and for the following seven weeks until 50% anthesis. Flat treatments were under water most of the time, while bedded treatments were sometimes above water. Seedling mortality in bedded treatments may have resulted from salt accumulation toward the center rows increased by evapotranspiration on surface. Water salinity dropped by the beginning of the reproductive stage (7^{e} week) which is one of the most sensitive phase of rice to salinity. Thus, water management is necessary to control evaporation during early seedling stage to reduce soil concentration therefore plant lost if rice is cultivated in beds.

Planting method did not significantly effect on rice yield despite their effects on soil chemical properties and plant nutrient uptake. In saline-sodic environment flat treatment would be more appropriate unless beds are under water to minimized salt concentration and therefore yield reduction. The effect of planting methods was more pronounced on soil EC and SAR which decrease respectively to below 4 dS m^{-1} and 13 in flat treatments after harvest. In addition, the higher availability of P, Mn and Zn in flat compared to bedded treatments resulted in high leaf P, Mn and Zn concentrations of plants in flat treatments. Phosphorus and Zn in particular become more available with increasing pH while Mn tend to increase at low pH. Biochar and shell amendments did not affect rice yield in 2014 even though soil CEC, C and pH were increased. However, we see significant differences among amendments in 2015 with biochar treatment having a higher yield compared to the control (25 % higher). Our results show that management practices that minimize salinity stress are crucial for achieving acceptable rice yield in acid, saline-sodic lowland production systems.

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List of Tables and Figures

Table 1: Characterization of biochar from *Eucalyptus camaldulensis*

Moisture	**Ash**	**C**	**N**	**C/N ratio**	**NO$_3^-$-N**	**NH$_4^+$-N**	**CEC**	
%					μg g^{-1}		meq 100g^{-1}	
4.29	67.68	16.24	0.16	104.42	1.55	0.13	44.32	
Ca	**K**	**Mg**	**Na**	**Total P**	**Total Ca**	**Total K**	**Total Mg**	**Total Na**
cmol+ kg^{-1}				mg kg^{-1}				
133.67	4	8.94	1.27	1730	9043	9089	2275	458

Table 2: Oyster Shell Characterization

Tests	Value (%)
Percent Passing 20 mesh	83.6
Percent Passing 60 mesh	48.7
Percent Passing 100 mesh	38.8
Effective CaCO3 Equivalent	61.89
Moisture (Oven 105 ^{o}C)	0.23
$CaCO_3$ Equivalent	102
Moisture (Oven 105 ^{o}C)	0.42

Table 3: Soil profile description in lowland rice paddy at Djibelor, Southern Senegal, in July 2014. Samples were collected at 12°34’16.46’’ N, 16°18’32.43’’ W.

Horizons	**Upper depth**	**Lower depth**	**Boundary distinctness**	**Texture class**	**Hue V/C**	**Structure**			**Moist consistence**	**Redoximorphic Features**	
	cm					**grade**	**size**	**shape**		concentrations	depletions
Apnz	0	10	abrupt smooth	FSL	10YR 4/1	structureless	massive		very friable	1% 2.5YR 4/6 Fe pore linings and soft masses	----
Apnz	10	22	abrupt smooth	FSL	10YR 4/1	weak	thick	platy	very friable	3% 2.5YR 4/6 Fe pore linings and soft masses	2% N 4/0 and 5Y 4/1 depletion zones
2Btng1	22	40	clear wavy	SCL	10YR 5/1	moderate	medium	sub angular blocky	firm	5% 7.5YR 5/6 and 5% 5YR 5/6 soft Fe masses, 5% 2.5YR 4/6 and 10R 3/6 soft Fe masses and pore linings	12% 2.5Y 8/1, 3% N 4/0 and 2% 5Y 4/1 depletion zones
2Btng2	40	55	clear wavy	SCL	2.5Y 5/2	moderate	medium	sub angular blocky	friable	5% 7.5YR 5/6 and 5YR 5/6 soft Fe masses, 15% 2.5YR 3/6 and 10R 4/6 soft Fe masses and pore linings	12% 2.5Y 8/1 and 5% 2.5Y 6/1 depletion zones
2BCngz	55	79	clear smooth	FSL	2.5Y 4/2	weak	medium	sub angular blocky	friable	15% 7.5YR 5/6, 5YR 5/6, and 2.5YR 3/6 soft Fe masses and pore linings	5% 2.5Y 8/1 and 5% N 4/0 depletion zones
3Cgz1	79	99	clear smooth	LFS	N 4/0	structureless	massive		very friable	5% 10YR 4/4, 5% 10YR 5/3, 5% 10YR and 2.5Y 6/6, and 5% 7.5YR 5/4 soft Fe masses and pore linings	10% N 6/0 depletion zones
3Cgz2	99	130	--	LFS	N 4/0	structureless	massive		very friable	55% 10YR 4/4, 5% 10YR 5/3, 5% 10YR and 2.5Y 6/6, and 5% 7.5YR 5/4 soft Fe masses and pore linings	10% N 6/0 depletion zones

Table 4: Physical and Chemical Properties of the Soil Profile Djibelor, Southern Senegal, in July 2014. Samples were collected at 12°34’16.46’’ N, 16°18’32.43’’ W.

Horizons	pH†	SAR†	EC_e†	Na†	C	N‡	P	K	Ca	Mg	Fe	Mn	Zn	B	CEC	Al	H	S
			dS m^{-1}	mg L^{-1}	g kg^{-1}	------------------------------------mg kg^{-1}--									-------cmol+ kg^{-1}-------			%
Apnz	3.47	43.3	55.54	14171.2	70.9	5543.15	2	95	275	1018	55.5	2.2	2.2	0.4	12.6	0.7485	6.6	0.12
Apnz	3.68	31.7	15.31	3447.73	37.6	4059.49	2	67	94	231	26.7	0.5	1.3	0.4	3.8	0.4491	1.4	0.07
2Btng1	3.63	30.2	16.7	3427.44	29.5	4230.12	1	123	200	392	18.2	0.8	5.3	0.8	7.2	0.4491	5	0.09
2Btng2	3.45	33.3	27.7	5336.47	23.4	3427.76	1	125	230	415	23.3	0.8	5.7	0.8	7.1	0.7485	9.4	0.05
2BCngz	4.9	34.7	33.35	6591.25	26.8	3330.81	1	125	407	475	26.1	0.8	6.8	0.9	7.4	0.1497	6.6	0.24
3Cgz1	2.73	32.4	55.3	7155.69	36.2	3403.50	6	10	716	702	245.4	1.3	14.7	0.2	14.9	3.7425	15.2	0.25
3Cgz2	2.39	27.2	62.4	4869.13	36.5	3000.10	5	8	297	885	934.7	2	9	0.1	17.8	8.2335	10.2	0.58

† Soil pH, EC_e, SAR, and Na were analyzed based on the saturated paste extract

‡ N, P, K, Ca, Mg, Fe, Mn, Zn, and B were analyzed in a Mehlich 1 extract; Al in a KCl extract, H in a $BaCl_2$ extract, and S by high temperature dry combustion using LECO S analyzer

Table 5: ANOVA for WAR 1 rice yield and phenological parameters in 2014 and 2015

		2014					2015				
Sources	**df**	**Yield**	**Tillers**	**Panicles**	**Straw**	**Height**	**Yield**	**Tillers**	**Panicles**	**Height**	**Straw**
		t ha^{-1}	m^{-2}		g m^{-2}	cm	t ha^{-1}	m^{-2}		cm	g m^{-2}
Planting Methods (PMs)	1	NS	**	**	NS	NS	NS	NS	NS	**	NS
Amendments (AMDs)	3	NS	**	**	NS	NS	*	NS	NS	NS	NS
PMs×AMDs	3	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
Reps	5	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
WP Error	5	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Covariate	1	**					*				
SP Error	30										

*Significant difference at $p = 0.05$

**Significant difference at $p = 0.01$

***Significant difference at $p = 0.001$

NS, not significant

Table 6: Mean separations for WAR1 yield and phenology in 2014 and 2015

Source	2014					2015				
	Yield	**Tillers**	**Panicles**	**Straw**	**Height**	**Yield**	**Tillers**	**Panicles**	**Straw**	**Height**
	t ha^{-1}	m^{-2}		g m^{-2}	cm	t ha^{-1}	m^{-2}		g m^{-2}	cm
Planting Methods										
Flat (F)	5.03 a	219 b	177 b	489 a	104.6 a	2.85 a	244 a	198 a	1706 a	152.1 a
Bed (Bd)	3.75 a	292 a	228 a	534 a	100.6 a	2.82 a	270 a	216 a	1856 a	133.8 b
Amendments										
Control (C)	4.71 a	279 a	214 ab	531 a	104.1 a	2.4 b	256 a	205 a	1971 a	141.7 a
Biochar (B)	4.67 a	246 ab	196 ab	453 a	101.8 a	3.18 a	272 a	223 a	1616 a	142.2 a
Shell (S)	3.78 a	276 a	229 a	568 a	102.4 a	3.01 ab	241 a	195 a	1592 a	143.3 a
Bioch+Sh (BS)	4.40 a	223 b	170 b	495 a	102.0 a	2.7 ab	272 a	205 a	1946 a	144.6 a
PMs×AMDs										
F×C	4.79 a	246 a	180 a	518 a	107.7 a	2.23 a	232 a	193 a	1892 a	147.8 abc
F×B	5.71 a	207 a	171 a	372 a	102.8 a	3.17 a	273 a	217 a	1233 a	144.6 abc
F×S	4.53 a	242 a	204 a	576 a	104.7 a	3.00 a	233 a	217 a	1608 a	155.9 ab
F×BS	5.20 a	182 a	151 a	491 a	103.3 a	2.99 a	238 a	193 a	2092 a	160.0 a
Bd×C	4.63 a	311 a	249 a	545 a	100.7 a	2.65 a	281 a	216 a	2050 a	135.6 bc
Bd×B	3.63 a	285 a	221 a	533 a	100.9 a	3.19 a	271 a	229 a	2000 a	139.8 abc
Bd×S	3.12 a	310 a	255 a	560 a	100.1 a	3.01 a	249 a	203 a	1575 a	130.7 c
Bd×BS	3.61 a	263 a	190 a	500 a	100.8 a	2.41 a	278 a	217 a	1800 a	129.1 c

Pairwise comparison of means with columns, according to Tukey HSD test (*p*=0.05)

Means with different letters are significant at (*p*=0.05)

Table 7: ANOVA for Soil Chemical Properties after 2014 rice growing season (Harvest)

Sources	df	pH	EC_e	SAR	C	N	P	K	Ca	Mg	Fe	Mn	Zn	B	CEC
			dS m^{-1}		g kg^{-1}	mg kg^{-1}									
Planting Methods (PMs)	1	**	*	**	NS	NS	NS	*	**	*	NS	*	*	NS	NS
Amendments (AMDs)	3	***	NS	NS	***	NS	*	NS	***	NS	NS	***	NS	***	***
PMs*AMDs	3	**	NS	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	**
Reps	5	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
WP Error	5	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SP Error	30														

*Significant differences at $p = 0.05$

**Significant differences at $p = 0.01$

***Significant differences at $p = 0.001$

NS, not significant

Table 8: Mean differences for soil chemical properties after 2014 rice growing season (Harvest)

Source	pH	EC_e	SAR	C	N	P	K	Ca	Mg	Fe	Mn	Zn	B	CEC
		dS m^{-1}		g kg^{-1}	mg kg-1									
Planting Methods														
Flat (F)	5.9 a	5.2 b	10.6 b	6.13 a	487.50 a	3.2 a	54.21 b	724.21 a	178.62 b	91 7 a	1.42 a	0.69 a	0.5 a	6.08 a
Bed (Bd)	5.0 b	14.6 a	21.3 a	5.38 a	479.16 a	2.6 a	64.92 a	399.67 b	275.33 a	74.9 a	1.1 b	0.53 b	0.6 a	5.50 a
Amendments														
Biochar (B)	4.5 b	10.9 a	18.1 a	6.65a	516.67 a	3.1 ab	62 a	208.67 b	244 a	80.2 a	1.42 ab	0.6 a	0.50 ab	4.67 b
Bioch+Sh (BS)	6.8 a	8.9 a	14.3 a	6.65 a	466.67 a	2.7 ab	60 a	983.08 a	205 a	83.7 a	1.76 a	0.6 a	0.59 a	7.00 a
Control (C)	4.1 b	9.9 a	16.3 a	4.83 b	466.67 a	2.3 b	53 a	150.17 b	219 a	71.5 a	0.84 c	0.5 a	0.40 b	4.33 b
Shell (S)	6.4 a	9.8 a	15.2 a	5.24 b	483.33 a	3.5 a	64 a	905.83 a	240 a	97.8 a	1.02 bc	0.8 a	0.61 a	7.16 a
PMs*AMDs														
F - B	4.7 cd	5.8 a	13.8 a	7.05 a	533.33 a	3.5 a	60 a	203.67 b	190 a	86.9 a	1.6 a	0.7 a	0.5 a	4.10 c
F - BS	7.7 a	3.7 a	7.0 a	7.30 a	483.33 a	3.0 a	54 a	1311.67 a	164 a	87.9 a	2.1 a	0.6 a	0.5 a	8.10 ab
F - C	4.1 d	4.1 a	11.1 a	4.62 a	450.00 a	2.3 a	45 a	132.00 b	151 a	73.4 a	0.8 a	0.4 a	0.3 a	3.70 c
F - S	7.1 ab	7.0 a	10.6 a	5.53 a	483.33 a	4.0 a	58 a	1249.5 a	210 a	118.7 a	1.2 a	1.1 a	0.6 a	8.42 a
Bd - B	4.3 d	16.1 a	22.2 a	5.88 a	500.00 a	2.7 a	63 a	213.67 b	298 a	73.4 a	1.3 a	0.6 a	0.5 a	5.23 bc
Bd - BS	5.9 bc	14.0 a	21.6 a	5.63 a	450.00 a	2.5 a	66 a	654.5 b	247 a	79.5 a	1.4 a	0.5 a	0.6 a	5.90 abc
Bd - C	4.2 d	15.7 a	19.9 a	5.03 a	483.00 a	2.2 a	62 a	168.33 b	288 a	69.6 a	0.9 a	0.5 a	0.5 a	4.97 c
Bd - S	5.7 c	12.5 a	21.5 a	4.95 a	483.33 a	3.0 a	69 a	562.17 b	269 a	76.9 a	0.9 a	0.5 a	0.6 a	5.90 abc

Pairwise comparison of means with columns, according to Tukey HSD test (*p*=0.05)

Means with different letters are significant at (*p*=0.05)

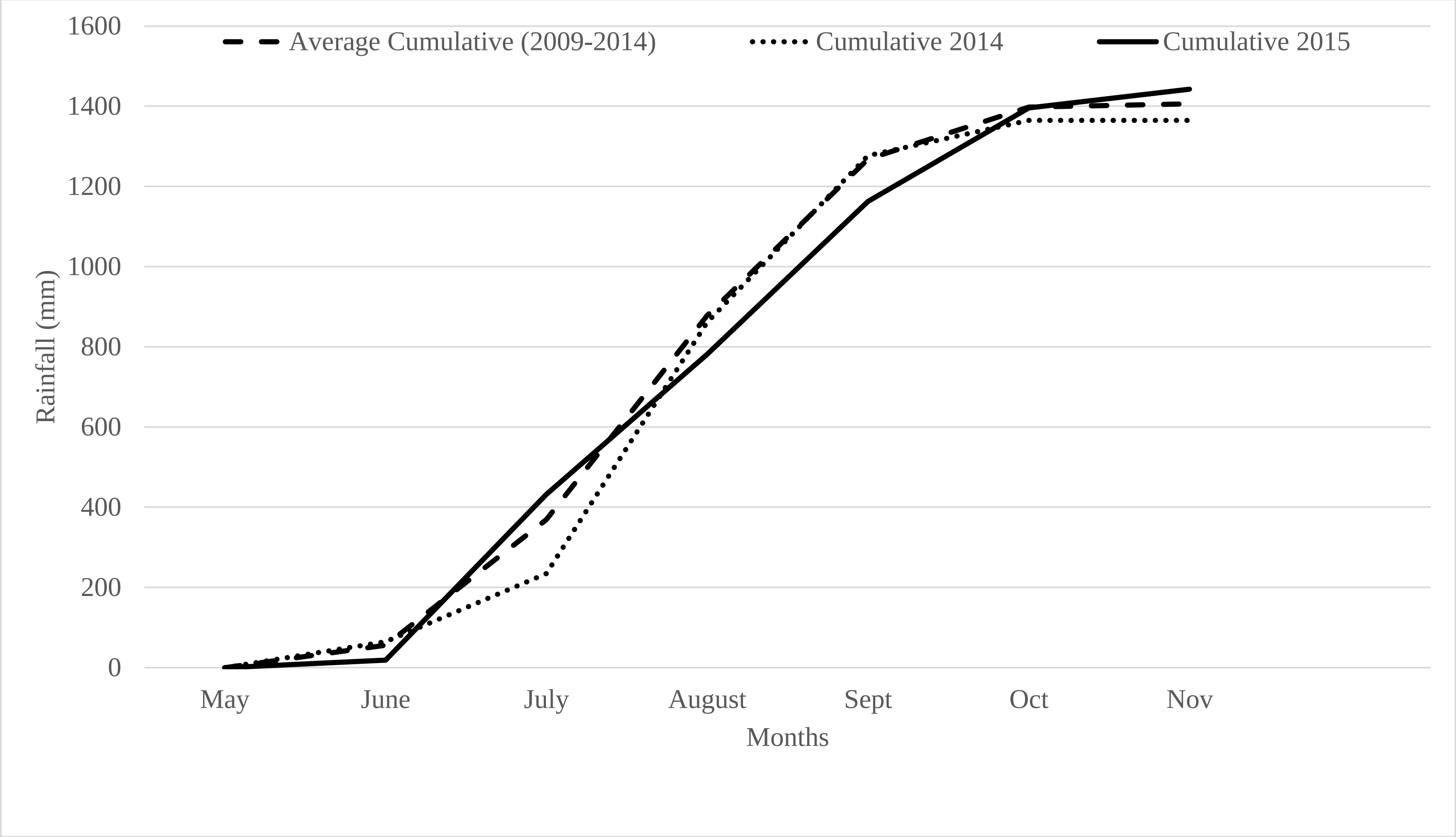

Figure 1: Average Cumulative Rainfall 2009-2015 and rainfall during 2014 and 2015 growing seasons at the experimental site near Djibelor, Senegal.

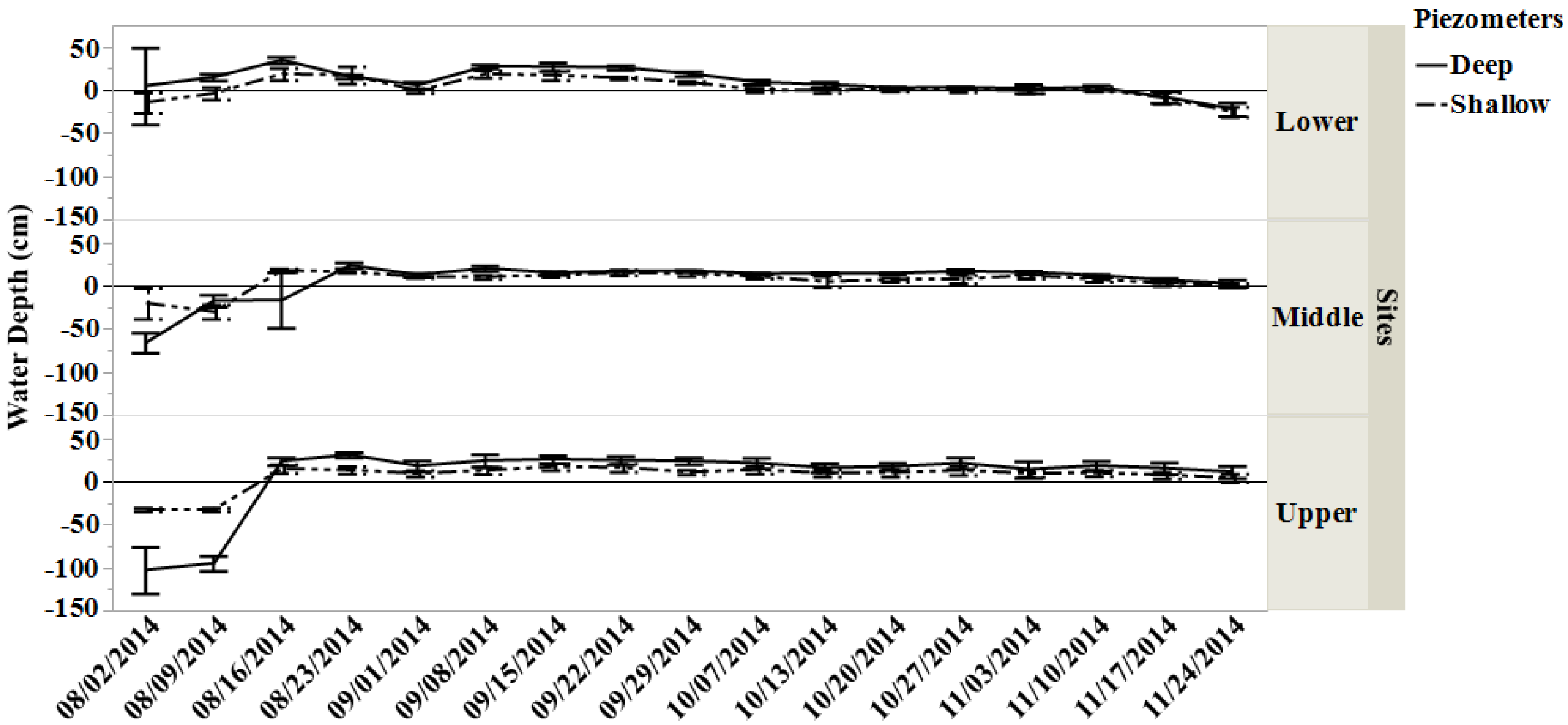

Figure 2: Groundwater depth in deep and shallow piezometers at 3 different positions (lower, middle and upper) at Djibelor Research site. Water depth was monitored weekly. The reference bars at 0 correspond to the ground level

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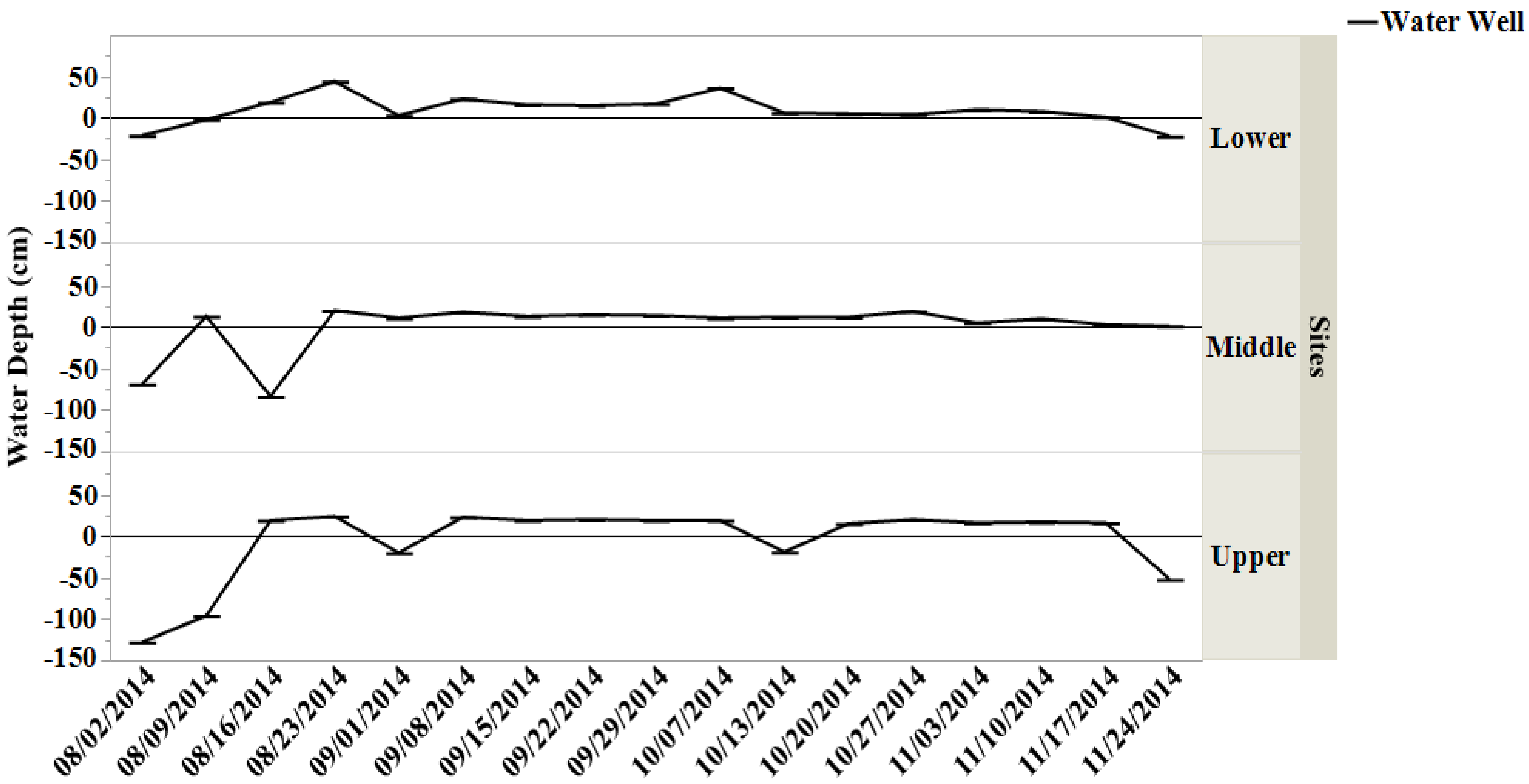

Figure 3: Groundwater depth in wells 3 different positions (lower, middle and upper) at Djibelor Research site. Water depth was monitored weekly. The reference bars at 0 correspond to the ground level

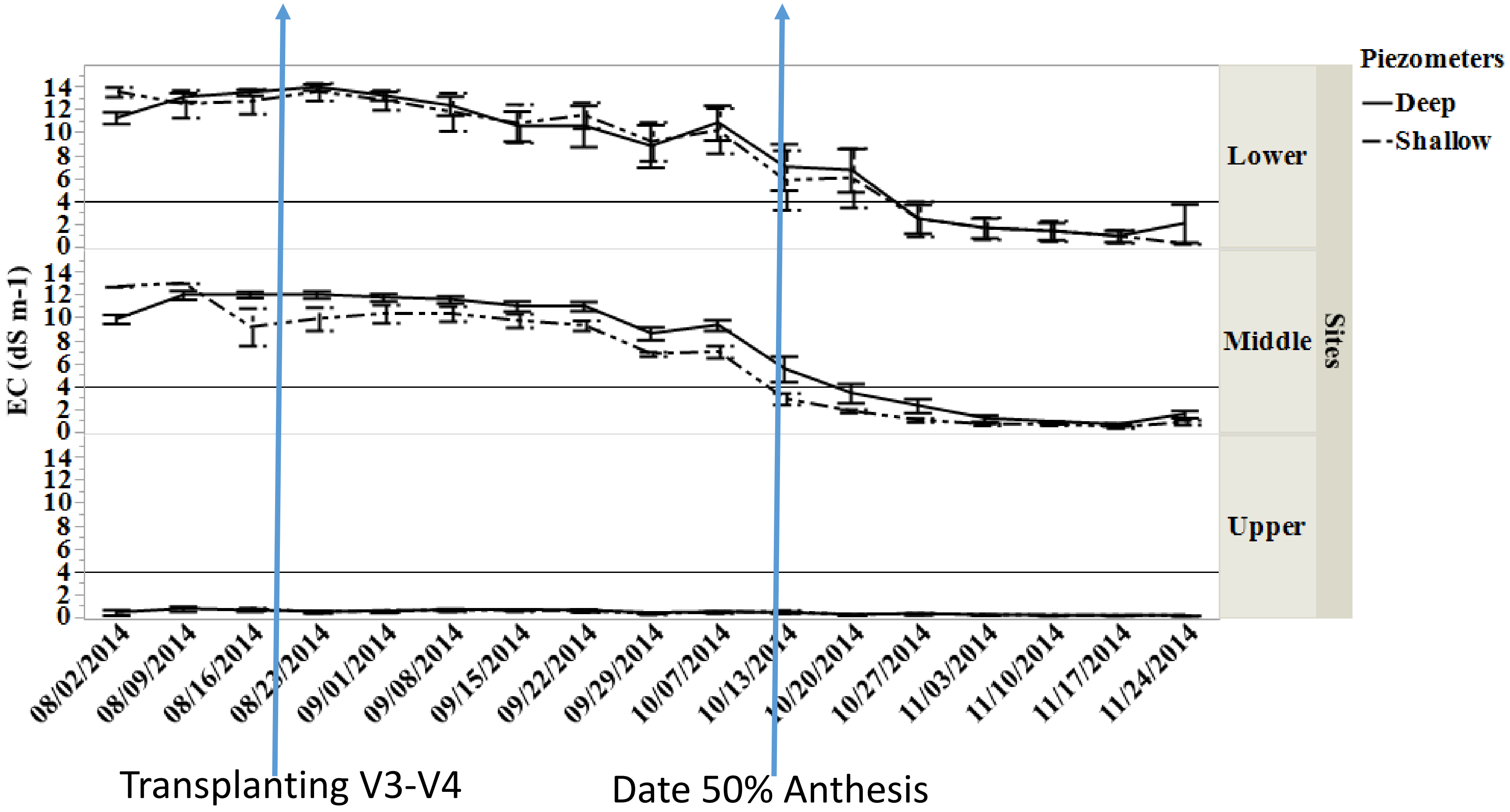

Figure 4: Groundwater EC in deep and shallow piezometers 3 different positions (lower, middle and upper) at Djibelor Research site. The EC was monitored weekly. The reference bars at 4 dS m-1 correspond to the EC threshold

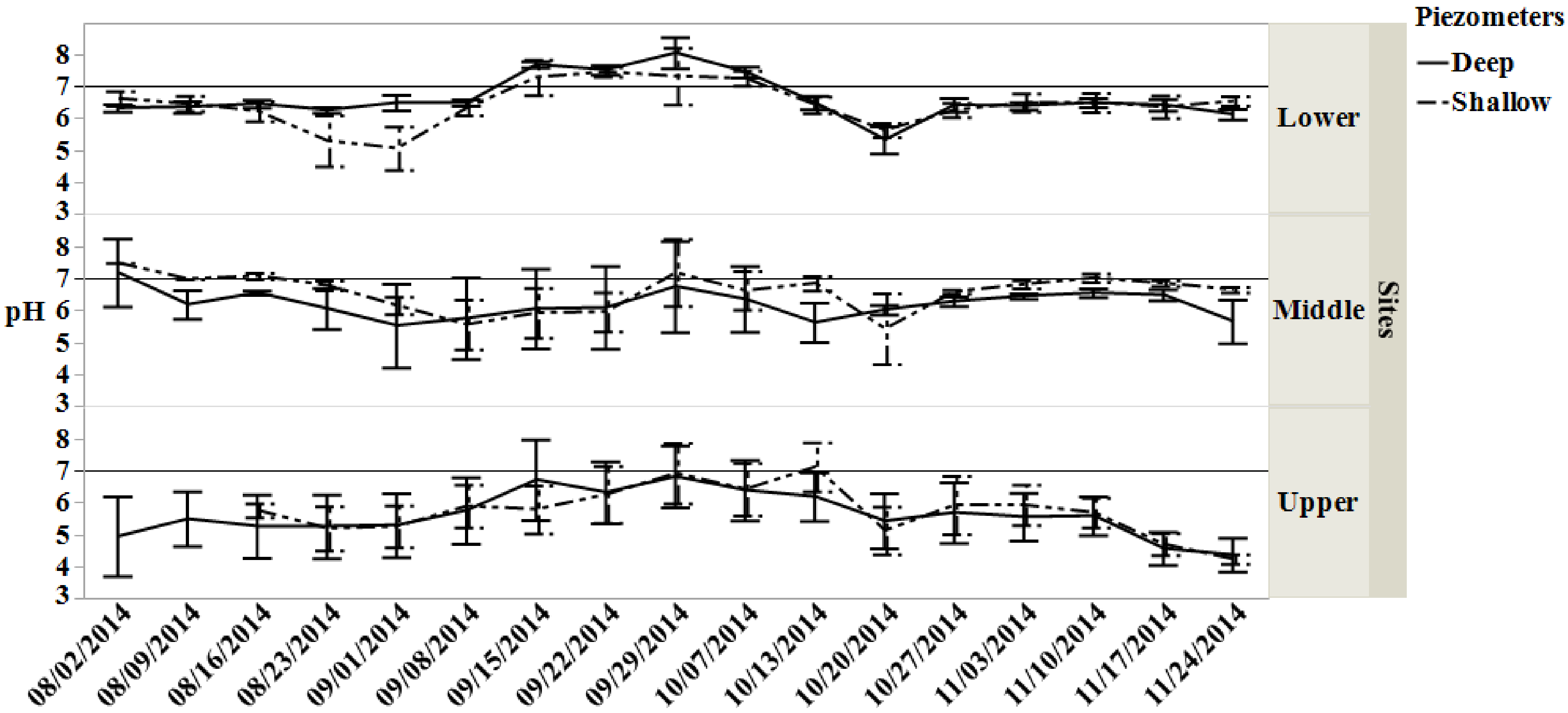

Figure 5: Groundwater pH in deep and shallow piezometers 3 different positions (lower, middle and upper) at Djibelor Research site. The pH was monitored weekly. The reference bars at 7 correspond to the pH threshold

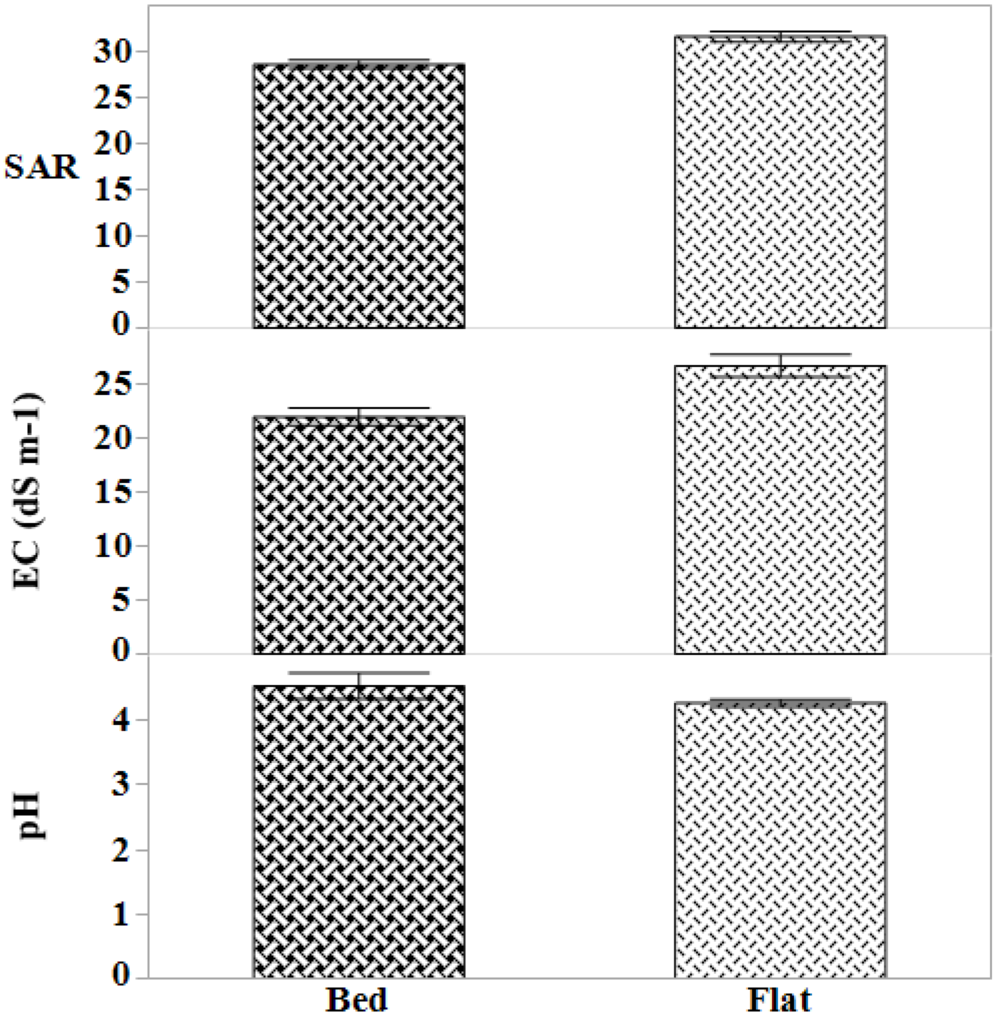

Figure 6: Soil pH, EC, and SAR (Saturated paste method) after tillage of the Rice Field (lower site) in Djibelor prior to adding amendments and transplanting in 2014

Figure 7: Soil Profile in the lower site (Location of our study plots)

Appendices:

Appendix 1: Rice tissues (Y-leaves and grains) nutrient analysis

Source (Leaves)	**df**	**N**	**P**	**K**	**Mg**	**Ca**	**S**	**Na**	**B**	**Zn**	**Mn**	**Fe**	**Cu**	**Al**
		------------------%------------------							**----------mg kg^{-1}----------**					
PMs	1	NS	**	NS	NS	NS	NS	NS	NS	*	*	NS	NS	NS
AMDs	3	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
PMs*AMDs	3	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Reps	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
WP Error	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SP Error	12													
Source (Grains)														
PMs	1	NS	NS	NS	NS	NS	*	NS	NS	*	NS	NS	NS	**
AMDs	3	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
PMs*AMDs	3	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Reps	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
WP Error	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SP Error	12													

Y-leaves were sampled at panicle differentiation

50 g grains were weighted at harvest

Appendix 2:

In 2014, rice yield was not significant across planting method and amendment treatments. This lack of statistical difference led us to conduct a follow up experiment in 2015. That experiment was initiated to identify yield-maximizing rates of biochar, shell, and biochar+shell. Therefore, 5 rates of biochar (0, 15, 30 and 45 t ha^{-1}), 10 rates of shell (0 to 9 t ha^{-1}) and 10 rates of biochar+shell (18 t biochar ha^{-1} + 0 to 9 t shell ha^{-1}) were studied separately and were randomly applied. The relationship between yield and amendment rates follow a quadratic fit as shown in figures A and B. In figure A, the R^2 is 26.7 % and biochar rate 15 t ha^{-1} has the maximum yield 4.83 t ha^{-1} compared to the control which has the lowest yield of 2.83 t ha^{-1}. Yield declined after the 15 t of biochar ha^{-1} but was not as low as in control. In figure B, there is not a strong relationship between yield and shell or biochar+shell rates and the R^2 of both treatment rates were 10 %. From these results, were conclude that biochar application at 15 t ha^{-1} will give better yield compared to other biochar rates (0, 30 and 45 t ha^{-1}), shell and biochar+shell treatment rates. In addition, rice yield in main experiment in 2015 showed that yield was 24.5 % higher in biochar amended plots compared to control.

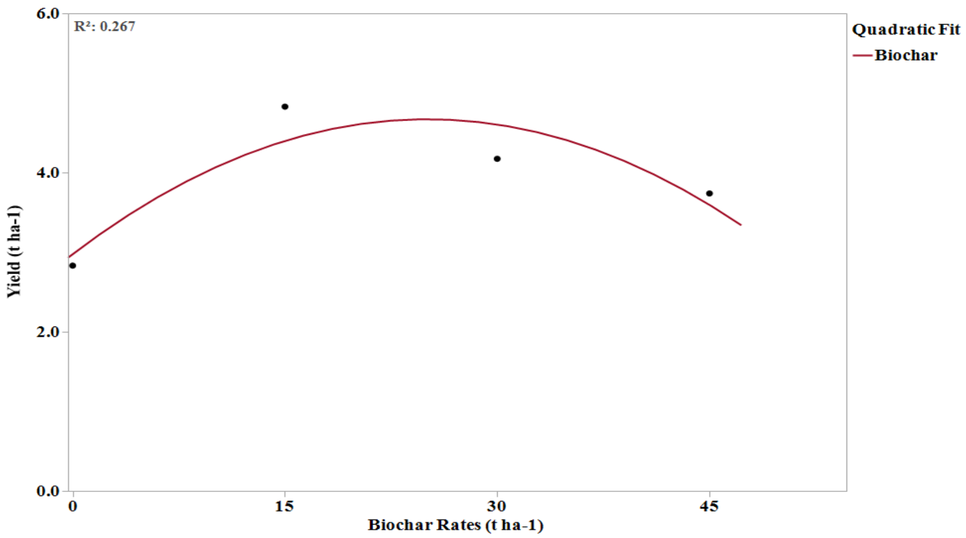

Figure A: Relationship between rice yield and biochar rates

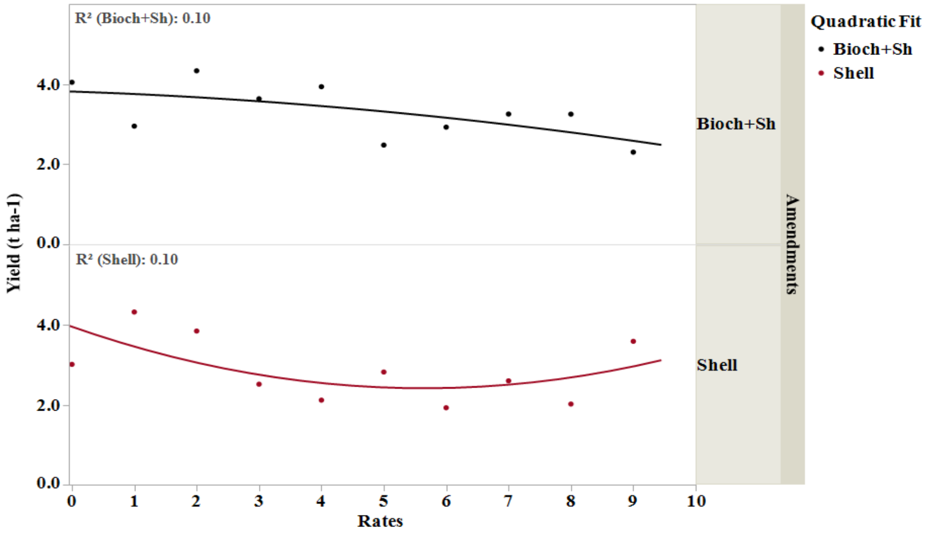

Figure B: Relationship between rice yield and shell, biochar+shell rates

Appendix 3: Soil data at harvest (1)

Plots_ID	**Reps**	**PMs**	**AMDs**	**PMs×AMDs**	**pH**	**EC**	**SAR**	**Est. ESP**	**C**	**N**	**P**	**K**
						dS m^{-1}		**%**	**g kg^{-1}**	**mg kg^{-1}**		
FB1	4	F	B	F×B	4.77	3.51	15.47	17.74	6.39	503.37	3.00	55.00
FB2	6	F	B	F×B	4.45	8.83	16.74	18.98	6.35	447.12	3.00	59.00
FB3	1	F	B	F×B	4.60	5.83	14.85	17.11	5.95	470.49	3.00	59.00
FB4	2	F	B	F×B	5.58	4.73	13.70	15.93	6.52	527.62	5.00	67.00
FB5	5	F	B	F×B	4.63	9.30	16.16	18.42	8.89	623.80	4.00	66.00
FB6	3	F	B	F×B	4.29	2.50	6.41	7.57	8.25	660.27	3.00	53.00
FBS1	4	F	BS	F×BS	7.72	8.87	15.07	17.33	6.28	446.20	4.00	69.00
FBS2	3	F	BS	F×BS	7.44	2.53	4.86	5.58	6.85	513.14	3.00	54.00
FBS3	5	F	BS	F×BS	7.60	1.51	3.31	3.49	7.01	496.95	2.00	46.00
FBS4	6	F	BS	F×BS	7.99	3.52	7.21	8.58	9.61	613.62	3.00	59.00
FBS5	2	F	BS	F×BS	7.51	3.34	8.59	10.24	7.97	496.27	3.00	59.00
FBS6	1	F	BS	F×BS	8.04	2.56	3.01	3.08	5.97	393.57	3.00	35.00
FC1	4	F	C	F×C	4.09	6.00	18.22	20.39	4.62	437.10	2.00	58.00
FC2	6	F	C	F×C	4.20	0.67	4.37	4.93	4.01	365.18	2.00	25.00
FC3	3	F	C	F×C	4.13	1.24	8.07	9.62	5.53	537.63	2.00	52.00
FC4	2	F	C	F×C	4.21	6.96	10.93	12.94	4.67	466.60	3.00	43.00
FC5	5	F	C	F×C	3.92	1.52	6.01	7.07	5.14	458.47	3.00	36.00
FC6	1	F	C	F×C	4.05	8.32	18.82	20.95	3.82	399.90	2.00	56.00
FS1	6	F	S	F×S	6.67	8.41	11.89	14.00	5.49	519.22	3.00	56.00
FS2	4	F	S	F×S	6.95	1.46	6.87	8.15	5.06	487.66	2.00	51.00
FS3	1	F	S	F×S	6.99	10.35	11.67	13.76	6.42	542.49	3.00	68.00
FS4	5	F	S	F×S	7.50	8.23	15.26	17.53	5.01	385.15	7.00	61.00
FS5	2	F	S	F×S	7.76	1.51	3.06	3.16	4.78	435.53	3.00	32.00
FS6	3	F	S	F×S	6.70	12.14	14.59	16.85	6.39	594.94	6.00	82.00

Appendix 4: Soil data at harvest (2)

Plots_ID	Reps	PMs	AMDs	PMs×AMDs	pH	EC	SAR	Est. ESP	C	N	P	K
						dS m^{-1}		%	g kg^{-1}	mg kg^{-1}		
RdB1	6	Bd	B	Bd×B	4.23	8.97	15.92	18.18	8.75	680.89	2.00	51.00
RdB2	3	Bd	B	Bd×B	4.05	38.10	34.08	32.89	5.84	451.60	3.00	65.00
RdB3	1	Bd	B	Bd×B	4.22	23.80	27.67	28.34	4.95	447.07	3.00	82.00
RdB4	5	Bd	B	Bd×B	4.31	12.19	20.98	22.89	4.55	434.22	2.00	64.00
RdB5	4	Bd	B	Bd×B	4.46	3.94	11.24	13.28	6.13	465.38	3.00	52.00
RdB6	2	Bd	B	Bd×B	4.30	9.55	23.54	25.07	5.09	495.64	3.00	65.00
RdBS1	6	Bd	BS	Bd×BS	6.96	28.00	31.67	31.25	5.94	482.60	3.00	86.00
RdBS2	2	Bd	BS	Bd×BS	6.42	17.33	24.57	25.92	5.28	447.51	2.00	70.00
RdBS3	5	Bd	BS	Bd×BS	5.23	10.41	18.11	20.29	4.78	423.61	2.00	64.00
RdBS4	3	Bd	BS	Bd×BS	4.40	7.80	20.33	22.32	4.52	425.51	2.00	59.00
RdBS5	4	Bd	BS	Bd×BS	4.62	7.28	18.96	21.08	6.69	565.42	3.00	59.00
RdBS6	1	Bd	BS	Bd×BS	7.55	13.41	16.05	18.31	6.56	431.65	3.00	57.00
RdC1	5	Bd	C	Bd×C	4.29	8.05	19.48	21.55	4.42	413.61	2.00	57.00
RdC2	3	Bd	C	Bd×C	4.08	14.98	22.78	24.44	5.46	533.75	2.00	71.00
RdC3	2	Bd	C	Bd×C	4.19	15.91	21.59	23.42	5.76	588.28	2.00	73.00
RdC4	6	Bd	C	Bd×C	4.04	11.07	21.31	23.18	4.21	387.93	2.00	48.00
RdC5	4	Bd	C	Bd×C	4.04	1.46	6.90	8.18	5.01	489.95	2.00	50.00
RdC6	1	Bd	C	Bd×C	4.34	43.00	36.61	34.53	5.27	537.88	3.00	71.00
RdS1	5	Bd	S	Bd×S	6.13	17.61	23.98	25.44	4.63	485.04	3.00	75.00
RdS2	1	Bd	S	Bd×S	7.00	12.56	17.89	20.09	5.30	528.84	2.00	73.00
RdS3	3	Bd	S	Bd×S	7.29	18.24	22.49	24.19	4.54	422.67	2.00	74.00
RdS4	6	Bd	S	Bd×S	4.47	17.07	27.24	28.02	5.87	577.53	3.00	82.00
RdS5	4	Bd	S	Bd×S	4.44	3.12	13.74	15.97	5.03	448.29	6.00	49.00
RdS6	2	Bd	S	Bd×S	5.18	6.45	13.97	16.21	4.43	452.53	2.00	61.00

Appendix 5: Soil data at harvest (3)

Plots_ID	Reps	PMs	AMDs	PMs×AMDs	Ca	Mg	Fe	Mn	Zn	Cu	B	Est. CEC	Mg:K	Ca:Mg	K:Mn
					mg kg^{-1}								Ratio		
FB1	4	F	B	F×B	169.00	168.00	91.90	1.30	0.50	0.20	0.50	3.40	3.05	1.01	42.31
FB2	6	F	B	F×B	192.00	229.00	69.70	2.10	0.50	0.30	0.40	4.20	3.88	0.84	28.10
FB3	1	F	B	F×B	172.00	199.00	93.50	1.00	0.80	0.30	0.50	3.70	3.37	0.86	59.00
FB4	2	F	B	F×B	157.00	195.00	77.70	0.70	0.80	0.20	0.50	4.10	2.91	0.81	95.71
FB5	5	F	B	F×B	285.00	207.00	99.90	2.30	1.00	0.60	0.60	4.60	3.14	1.38	28.70
FB6	3	F	B	F×B	247.00	143.00	88.60	1.90	0.40	0.30	0.40	4.60	2.70	1.73	27.89
FBS1	4	F	BS	F×BS	1,680.00	253.00	84.60	2.30	0.80	0.30	0.70	10.70	3.67	6.64	30.00
FBS2	3	F	BS	F×BS	1,286.00	154.00	82.80	1.90	0.50	0.30	0.50	8.00	2.85	8.35	28.42
FBS3	5	F	BS	F×BS	1,197.00	121.00	86.70	1.70	0.50	0.30	0.50	7.10	2.63	9.89	27.06
FBS4	6	F	BS	F×BS	1,478.00	185.00	99.40	2.50	0.70	0.30	0.60	9.10	3.14	7.99	23.60
FBS5	2	F	BS	F×BS	980.00	162.00	91.60	1.70	0.70	0.30	0.60	6.50	2.75	6.05	34.71
FBS6	1	F	BS	F×BS	1,249.00	106.00	82.30	2.70	0.40	0.30	0.40	7.20	3.03	11.78	12.96
FC1	4	F	C	F×C	98.00	188.00	75.50	0.60	0.60	0.20	0.40	3.70	3.24	0.52	96.67
FC2	6	F	C	F×C	140.00	89.00	76.40	0.90	0.20	0.30	0.20	3.30	3.56	1.57	27.78
FC3	3	F	C	F×C	118.00	134.00	78.10	0.80	0.30	0.30	0.30	3.80	2.58	0.88	65.00
FC4	2	F	C	F×C	171.00	196.00	84.40	1.00	0.60	0.20	0.40	3.90	4.56	0.87	43.00
FC5	5	F	C	F×C	162.00	97.00	70.90	1.00	0.30	0.30	0.20	3.90	2.69	1.67	36.00
FC6	1	F	C	F×C	103.00	200.00	55.00	0.70	0.40	0.20	0.40	3.60	3.57	0.52	80.00
FS1	6	F	S	F×S	840.00	246.00	110.80	1.40	1.00	0.30	0.60	7.00	4.39	3.41	40.00
FS2	4	F	S	F×S	660.00	141.00	77.30	0.80	0.60	0.60	0.50	5.20	2.76	4.68	63.75
FS3	1	F	S	F×S	1,549.00	282.00	158.60	1.60	1.40	0.30	0.80	10.30	4.15	5.49	42.50
FS4	5	F	S	F×S	1,589.00	217.00	69.70	1.10	0.50	0.30	0.60	9.90	3.56	7.32	55.45
FS5	2	F	S	F×S	1,931.00	104.00	89.30	0.90	0.50	0.30	0.50	10.60	3.25	18.57	35.56
FS6	3	F	S	F×S	928.00	271.00	206.30	1.30	2.50	0.30	0.80	7.50	3.30	3.42	63.08

Appendix 6: Soil data at harvest (4)

Plots_ID	Reps	PMs	AMDs	PMs×AMDs	Ca	Mg	Fe	Mn	Zn	Cu	B	Est. CEC	Mg:K	Ca:Mg	K:Mn
					mg kg^{-1}								Ratio		
RdB1	6	Bd	B	Bd×B	289.00	227.00	122.20	1.90	0.70	0.40	0.60	5.50	4.45	1.27	26.84
RdB2	3	Bd	B	Bd×B	288.00	476.00	78.30	1.90	0.80	0.20	0.60	7.20	7.32	0.61	34.21
RdB3	1	Bd	B	Bd×B	178.00	421.00	48.10	1.00	0.60	0.30	0.60	6.10	5.13	0.42	82.00
RdB4	5	Bd	B	Bd×B	134.00	282.00	42.30	0.70	0.50	0.30	0.40	4.40	4.41	0.48	91.43
RdB5	4	Bd	B	Bd×B	249.00	169.00	76.30	1.60	0.30	0.30	0.40	4.20	3.25	1.47	32.50
RdB6	2	Bd	B	Bd×B	144.00	211.00	73.30	0.70	0.50	0.30	0.50	4.00	3.25	0.68	92.86
RdBS1	6	Bd	BS	Bd×BS	768.00	385.00	123.40	1.20	0.60	0.30	1.00	7.30	4.48	1.99	71.67
RdBS2	2	Bd	BS	Bd×BS	672.00	280.00	62.50	1.20	0.50	0.30	0.60	5.90	4.00	2.40	58.33
RdBS3	5	Bd	BS	Bd×BS	446.00	215.00	71.80	1.20	0.50	0.30	0.60	4.40	3.36	2.07	53.33
RdBS4	3	Bd	BS	Bd×BS	143.00	181.00	52.80	0.60	0.40	0.30	0.40	3.40	3.07	0.79	98.33
RdBS5	4	Bd	BS	Bd×BS	180.00	177.00	80.90	1.30	0.40	0.30	0.50	3.70	3.00	1.02	45.38
RdBS6	1	Bd	BS	Bd×BS	1,718.00	245.00	85.70	2.80	0.70	0.20	0.70	10.70	4.30	7.01	20.36
RdC1	5	Bd	C	Bd×C	136.00	210.00	44.10	0.60	0.50	0.30	0.40	3.70	3.68	0.65	95.00
RdC2	3	Bd	C	Bd×C	175.00	330.00	66.40	0.80	0.60	0.30	0.50	5.60	4.65	0.53	88.75
RdC3	2	Bd	C	Bd×C	216.00	376.00	77.10	1.20	0.70	0.30	0.60	6.20	5.15	0.57	60.83
RdC4	6	Bd	C	Bd×C	144.00	202.00	57.70	0.70	0.40	0.20	0.40	3.90	4.21	0.71	68.57
RdC5	4	Bd	C	Bd×C	126.00	123.00	72.20	0.80	0.30	0.30	0.30	3.90	2.46	1.02	62.50
RdC6	1	Bd	C	Bd×C	213.00	484.00	100.30	1.00	0.70	0.20	0.70	6.50	6.82	0.44	71.00
RdS1	5	Bd	S	Bd×S	687.00	347.00	62.60	0.80	0.60	0.30	0.60	6.80	4.63	1.98	93.75
RdS2	1	Bd	S	Bd×S	784.00	327.00	65.80	0.90	0.50	0.30	0.60	7.10	4.48	2.40	81.11
RdS3	3	Bd	S	Bd×S	853.00	339.00	73.50	0.90	0.60	0.30	0.70	7.30	4.58	2.52	82.22
RdS4	6	Bd	S	Bd×S	377.00	293.00	76.60	0.70	0.70	0.20	0.80	6.20	3.57	1.29	117.14
RdS5	4	Bd	S	Bd×S	214.00	131.00	82.00	1.10	0.30	0.30	0.30	3.40	2.67	1.63	44.55
RdS6	2	Bd	S	Bd×S	458.00	177.00	100.90	0.80	0.40	0.30	0.50	4.60	2.90	2.59	76.25

Appendix 7: Soil data at harvest (5)

Plots_ID	Reps	PMs	AMDs	PMs×AMDs	P_Rating	K_Rating	Ca_Rating	Mg_Rating	SS_Rating	OM_Rating
FB1	4	F	B	F×B	L	M	L	VH	L	L
FB2	6	F	B	F×B	L	M	L	VH	H	L
FB3	1	F	B	F×B	L	M	L	VH	M	L
FB4	2	F	B	F×B	L+	M	L	VH	M	L
FB5	5	F	B	F×B	L	M	L+	VH	H	M
FB6	3	F	B	F×B	L	M	L+	VH	L	M
FBS1	4	F	BS	F×BS	L	M	VH	VH	H	L
FBS2	3	F	BS	F×BS	L	M	VH	VH	L	M
FBS3	5	F	BS	F×BS	L	M-	VH	VH	L	M
FBS4	6	F	BS	F×BS	L	M	VH	VH	M	M
FBS5	2	F	BS	F×BS	L	M	H+	VH	M	M
FBS6	1	F	BS	F×BS	L	L+	VH	H+	L	L
FC1	4	F	C	F×C	L	M	L-	VH	H	L
FC2	6	F	C	F×C	L-	L	L	H	L	L
FC3	3	F	C	F×C	L	M	L-	VH	L	L
FC4	2	F	C	F×C	L	M-	L	VH	H	L
FC5	5	F	C	F×C	L	L+	L	H+	L	L
FC6	1	F	C	F×C	L	M	L-	VH	H	L
FS1	6	F	S	F×S	L	M	H-	VH	H	L
FS2	4	F	S	F×S	L-	M	M+	VH	L	L
FS3	1	F	S	F×S	L	M	VH	VH	H	L
FS4	5	F	S	F×S	M-	M	VH	VH	H	L
FS5	2	F	S	F×S	L	L+	VH	H+	L	L
FS6	3	F	S	F×S	M-	M+	H	VH	H	M

Appendix 8: Soil data at harvest (6)

Plots_ID	**Reps**	**PMs**	**AMDs**	**PMs×AMDs**	**P_Rating**	**K_Rating**	**Ca_Rating**	**Mg_Rating**	**SS_Rating**	**OM_Rating**
RdB1	6	Bd	B	Bd×B	L	M	L+	VH	H	M
RdB2	3	Bd	B	Bd×B	L	M	L+	VH	EH	M
RdB3	1	Bd	B	Bd×B	L	M+	L	VH	EH	M
RdB4	5	Bd	B	Bd×B	L	M	L	VH	H	L
RdB5	4	Bd	B	Bd×B	L	M	L+	VH	M	L
RdB6	2	Bd	B	Bd×B	L	M	L	VH	H	M
RdBS1	6	Bd	BS	Bd×BS	L	M+	H-	VH	EH	M
RdBS2	2	Bd	BS	Bd×BS	L	M	M+	VH	VH	L
RdBS3	5	Bd	BS	Bd×BS	L	M	M-	VH	H	L
RdBS4	3	Bd	BS	Bd×BS	L	M	L	VH	H	L
RdBS5	4	Bd	BS	Bd×BS	L	M	L	VH	H	L
RdBS6	1	Bd	BS	Bd×BS	L	M	VH	VH	H	L
RdC1	5	Bd	C	Bd×C	L	M	L	VH	H	L
RdC2	3	Bd	C	Bd×C	L	M	L	VH	VH	M
RdC3	2	Bd	C	Bd×C	L	M	L	VH	VH	M
RdC4	6	Bd	C	Bd×C	L-	M-	L	VH	H	L
RdC5	4	Bd	C	Bd×C	L	M-	L	VH	L	L
RdC6	1	Bd	C	Bd×C	L	M	L	VH	EH	L
RdS1	5	Bd	S	Bd×S	L	M	M+	VH	VH	L
RdS2	1	Bd	S	Bd×S	L	M	H-	VH	H	L
RdS3	3	Bd	S	Bd×S	L	M	H	VH	VH	L
RdS4	6	Bd	S	Bd×S	L	M+	M-	VH	VH	M
RdS5	4	Bd	S	Bd×S	L+	M-	L	VH	M	L
RdS6	2	Bd	S	Bd×S	L	M	M-	VH	H	L

Appendix 9: Rice Yield Components in 2014

Years	Plots_ID	WP	PMs	AMDs	PMs × AMDs	Panicle Emergence	Anthesis	Tillers	Panicles
						Date 50 %		m^{-2}	
2014	FB1	4	F	B	F×B	11/6/14	11/11/14	165	163
2014	FB2	6	F	B	F×B	11/9/14	11/14/14	153	118
2014	FB3	1	F	B	F×B	11/6/14	11/11/14	190	178
2014	FB4	2	F	B	F×B	11/6/14	11/12/14	288	220
2014	FB5	5	F	B	F×B	11/9/14	11/14/14	255	195
2014	FB6	3	F	B	F×B	11/6/14	11/10/14	193	150
2014	FBS1	4	F	BS	F×BS	11/6/14	11/11/14	180	160
2014	FBS2	3	F	BS	F×BS	11/9/14	11/15/14	213	162
2014	FBS3	5	F	BS	F×BS	11/6/14	11/10/14	150	122
2014	FBS4	6	F	BS	F×BS	11/6/14	11/12/14	215	183
2014	FBS5	2	F	BS	F×BS	11/6/14	11/10/14	163	137
2014	FBS6	1	F	BS	F×BS	11/6/14	11/10/14	170	143
2014	FC1	4	F	C	F×C	11/9/14	11/14/14	190	158
2014	FC2	6	F	C	F×C	11/6/14	11/10/14	235	178
2014	FC3	3	F	C	F×C	11/6/14	11/10/14	285	178
2014	FC4	2	F	C	F×C	11/6/14	11/10/14	257	212
2014	FC5	5	F	C	F×C	11/6/14	11/11/14	278	207
2014	FC6	1	F	C	F×C	11/3/14	11/7/14	233	147
2014	FS1	6	F	S	F×S	11/6/14	11/12/14	238	193
2014	FS2	4	F	S	F×S	11/6/14	11/10/14	240	180
2014	FS3	1	F	S	F×S	11/6/14	11/11/14	280	242
2014	FS4	5	F	S	F×S	11/3/14	11/7/14	193	170
2014	FS5	2	F	S	F×S	11/6/14	11/11/14	218	173
2014	FS6	3	F	S	F×S	11/9/14	11/15/14	285	268
2014	BdB1	6	Rd	B	Rd×B	11/3/14	11/10/14	338	260
2014	BdB2	3	Rd	B	Rd×B	11/6/14	11/10/14	292	233
2014	BdB3	1	Rd	B	Rd×B	11/9/14	11/14/14	292	222
2014	BdB4	5	Rd	B	Rd×B	11/6/14	11/10/14	280	228
2014	BdB5	4	Rd	B	Rd×B	11/11/14	11/14/14	248	180
2014	BdB6	2	Rd	B	Rd×B	11/6/14	11/10/14	257	203
2014	BdBS1	6	Rd	BS	Rd×BS	11/6/14	11/11/14	273	207
2014	BdBS2	2	Rd	BS	Rd×BS	11/9/14	11/13/14	250	182
2014	BdBS3	5	Rd	BS	Rd×BS	11/6/14	11/13/14	233	170
2014	BdBS4	3	Rd	BS	Rd-BS	11/3/14	11/8/14	233	187
2014	BdBS5	4	Rd	BS	Rd×BS	11/3/14	11/7/14	290	237
2014	BdBS6	1	Rd	BS	Rd×BS	11/6/14	11/11/14	302	155
2014	BdC1	5	Rd	C	Rd×C	11/6/14	11/11/14	253	202
2014	BdC2	3	Rd	C	Rd×C	11/9/14	11/14/14	355	277
2014	BdC3	2	Rd	C	Rd×C	11/9/14	11/14/14	275	225
2014	BdC4	6	Rd	C	Rd×C	11/3/14	11/8/14	375	317
2014	BdC5	4	Rd	C	Rd×C	11/3/14	11/8/14	258	168
2014	BdC6	1	Rd	C	Rd×C	11/6/14	11/12/14	352	302
2014	BdS1	5	Rd	S	Rd×S	11/9/14	11/14/14	417	340
2014	BdS2	1	Rd	S	Rd×S	11/9/14	11/13/14	262	220
2014	BdS3	3	Rd	S	Rd×S	11/9/14	11/14/14	310	243
2014	BdS4	6	Rd	S	Rd×S	11/6/14	11/12/14	355	315
2014	BdS5	4	Rd	S	Rd×S	11/6/14	11/11/14	295	247
2014	BdS6	2	Rd	S	Rd×S	11/3/14	11/7/14	223	162

Appendix 10: Rice Yield Components and Yield in 2014

Years	Plots_ID	WP	PMs	AMDs	PMs × AMDs	Straw	Height	Live Plants	Yield
						g m^{-2}	cm	%	t ha^{-1}
2014	FB1	4	F	B	F×B	260	117.5	29	8.93
2014	FB2	6	F	B	F×B	330	88.5	69	3.79
2014	FB3	1	F	B	F×B	340	97.5	50	4.17
2014	FB4	2	F	B	F×B	510	115.5	52	3.50
2014	FB5	5	F	B	F×B	475	95.5	33	4.69
2014	FB6	3	F	B	F×B	315	102	25	.
2014	FBS1	4	F	BS	F×BS	545	111	51	5.10
2014	FBS2	3	F	BS	F×BS	595	103.5	55	5.66
2014	FBS3	5	F	BS	F×BS	365	107	68	4.62
2014	FBS4	6	F	BS	F×BS	540	98.5	78	4.67
2014	FBS5	2	F	BS	F×BS	345	106	80	2.92
2014	FBS6	1	F	BS	F×BS	555	94	70	3.73
2014	FC1	4	F	C	F×C	485	96.5	79	2.96
2014	FC2	6	F	C	F×C	535	101	69	5.30
2014	FC3	3	F	C	F×C	505	109.5	90	3.20
2014	FC4	2	F	C	F×C	610	115	32	4.03
2014	FC5	5	F	C	F×C	430	120.5	71	4.41
2014	FC6	1	F	C	F×C	540	103.5	84	3.09
2014	FS1	6	F	S	F×S	435	108.5	36	4.29
2014	FS2	4	F	S	F×S	700	101.5	73	4.64
2014	FS3	1	F	S	F×S	540	113	38	3.47
2014	FS4	5	F	S	F×S	550	102.5	80	3.90
2014	FS5	2	F	S	F×S	640	107.5	71	4.78
2014	FS6	3	F	S	F×S	590	95	56	4.17
2014	BdB1	6	Rd	B	Rd×B	840	102.5	44	5.56
2014	BdB2	3	Rd	B	Rd×B	375	116	35	3.92
2014	BdB3	1	Rd	B	Rd×B	530	83.5	44	1.98
2014	BdB4	5	Rd	B	Rd×B	510	103	57	2.74
2014	BdB5	4	Rd	B	Rd×B	475	96.5	69	5.00
2014	BdB6	2	Rd	B	Rd×B	470	104	53	4.22
2014	BdBS1	6	Rd	BS	Rd×BS	660	96.5	31	4.55
2014	BdBS2	2	Rd	BS	Rd×BS	390	98.5	53	2.63
2014	BdBS3	5	Rd	BS	Rd×BS	555	100	58	2.11
2014	BdBS4	3	Rd	BS	Rd-BS	400	99	63	3.57
2014	BdBS5	4	Rd	BS	Rd×BS	750	101	69	5.56
2014	BdBS6	1	Rd	BS	Rd×BS	245	109.5	69	2.50
2014	BdC1	5	Rd	C	Rd×C	275	95	49	2.11
2014	BdC2	3	Rd	C	Rd×C	440	93	12	10.29
2014	BdC3	2	Rd	C	Rd×C	775	91.5	68	2.04
2014	BdC4	6	Rd	C	Rd×C	640	111.5	44	6.64
2014	BdC5	4	Rd	C	Rd×C	600	102.5	51	6.85
2014	BdC6	1	Rd	C	Rd×C	540	110.5	26	4.73
2014	BdS1	5	Rd	S	Rd×S	690	96.5	33	3.13
2014	BdS2	1	Rd	S	Rd×S	665	91	59	2.06
2014	BdS3	3	Rd	S	Rd×S	500	93	63	1.11
2014	BdS4	6	Rd	S	Rd×S	660	99.5	38	5.91
2014	BdS5	4	Rd	S	Rd×S	405	111	68	4.08
2014	BdS6	2	Rd	S	Rd×S	440	109.5	44	3.97

Appendix 11: Rice Yield Components in 2015

Years	Plots_ID	WP	PMs	AMDs	PMs × AMDs	Panicle Emergence	Anthesis	Tillers	Panicles
						Date 50 %		m^{-2}	
2015	FB1	4	F	B	F×B	11/5/15	11/10/15	270	212
2015	FB2	6	F	B	F×B	11/5/15	11/10/15	322	248
2015	FB3	1	F	B	F×B	11/5/15	11/10/15	298	245
2015	FB4	2	F	B	F×B	11/5/15	11/10/15	247	183
2015	FB5	5	F	B	F×B	11/5/15	11/10/15	233	190
2015	FB6	3	F	B	F×B	11/5/15	11/10/15	268	223
2015	FBS1	4	F	BS	F×BS	11/5/15	11/10/15	195	167
2015	FBS2	3	F	BS	F×BS	11/5/15	11/10/15	280	230
2015	FBS3	5	F	BS	F×BS	11/5/15	11/10/15	207	167
2015	FBS4	6	F	BS	F×BS	11/5/15	11/10/15	258	200
2015	FBS5	2	F	BS	F×BS	11/5/15	11/10/15	247	215
2015	FBS6	1	F	BS	F×BS	11/5/15	11/10/15	243	178
2015	FC1	4	F	C	F×C	11/5/15	11/10/15	220	192
2015	FC2	6	F	C	F×C	11/5/15	11/10/15	188	160
2015	FC3	3	F	C	F×C	11/5/15	11/10/15	272	238
2015	FC4	2	F	C	F×C	11/5/15	11/10/15	257	228
2015	FC5	5	F	C	F×C	11/5/15	11/10/15	243	168
2015	FC6	1	F	C	F×C	11/5/15	11/10/15	210	173
2015	FS1	6	F	S	F×S	11/5/15	11/10/15	255	205
2015	FS2	4	F	S	F×S	11/5/15	11/10/15	260	208
2015	FS3	1	F	S	F×S	11/5/15	11/10/15	193	158
2015	FS4	5	F	S	F×S	11/5/15	11/10/15	265	203
2015	FS5	2	F	S	F×S	11/5/15	11/10/15	220	188
2015	FS6	3	F	S	F×S	11/5/15	11/10/15	205	167
2015	BdB1	6	Rd	B	Rd×B	11/5/15	11/10/15	280	233
2015	BdB2	3	Rd	B	Rd×B	11/5/15	11/10/15	265	210
2015	BdB3	1	Rd	B	Rd×B	11/5/15	11/10/15	252	208
2015	BdB4	5	Rd	B	Rd×B	11/5/15	11/10/15	260	227
2015	BdB5	4	Rd	B	Rd×B	11/5/15	11/10/15	263	228
2015	BdB6	2	Rd	B	Rd×B	11/5/15	11/10/15	305	268
2015	BdBS1	6	Rd	BS	Rd×BS	11/5/15	11/10/15	283	185
2015	BdBS2	2	Rd	BS	Rd×BS	11/5/15	11/10/15	320	257
2015	BdBS3	5	Rd	BS	Rd×BS	11/5/15	11/10/15	292	223
2015	BdBS4	3	Rd	BS	Rd-BS	11/5/15	11/10/15	200	147
2015	BdBS5	4	Rd	BS	Rd×BS	11/5/15	11/10/15	305	247
2015	BdBS6	1	Rd	BS	Rd×BS	11/5/15	11/10/15	267	242
2015	BdC1	5	Rd	C	Rd×C	11/5/15	11/10/15	247	190
2015	BdC2	3	Rd	C	Rd×C	11/5/15	11/10/15	238	162
2015	BdC3	2	Rd	C	Rd×C	11/5/15	11/10/15	322	250
2015	BdC4	6	Rd	C	Rd×C	11/5/15	11/10/15	178	153
2015	BdC5	4	Rd	C	Rd×C	11/5/15	11/10/15	323	255
2015	BdC6	1	Rd	C	Rd×C	11/5/15	11/10/15	377	287
2015	BdS1	5	Rd	S	Rd×S	11/5/15	11/10/15	240	205
2015	BdS2	1	Rd	S	Rd×S	11/5/15	11/10/15	272	207
2015	BdS3	3	Rd	S	Rd×S	11/5/15	11/10/15	225	187
2015	BdS4	6	Rd	S	Rd×S	11/5/15	11/10/15	292	230
2015	BdS5	4	Rd	S	Rd×S	11/5/15	11/10/15	233	202
2015	BdS6	2	Rd	S	Rd×S	11/5/15	11/10/15	230	185

Appendix 12: Rice Yield Components and Yield in 2015

Years	Plots_ID	WP	PMs	AMDs	PMs × AMDs	Straw	Height	Live Plants	Yield
						g m^{-2}	cm	%	t ha^{-1}
2015	FB1	4	F	B	F×B	1000	136.5	33	2.34
2015	FB2	6	F	B	F×B	1900	154	80	3.25
2015	FB3	1	F	B	F×B	800	134.5	38	2.08
2015	FB4	2	F	B	F×B	800	143	51	2.81
2015	FB5	5	F	B	F×B	700	145	44	2.98
2015	FB6	3	F	B	F×B	2200	154.5	88	3.27
2015	FBS1	4	F	BS	F×BS	2200	157.5	85	3.05
2015	FBS2	3	F	BS	F×BS	2300	167.5	90	2.62
2015	FBS3	5	F	BS	F×BS	1500	160	96	3.53
2015	FBS4	6	F	BS	F×BS	2200	167.5	92	3.41
2015	FBS5	2	F	BS	F×BS	2350	157	93	4.07
2015	FBS6	1	F	BS	F×BS	2000	150.5	100	2.60
2015	FC1	4	F	C	F×C	1500	118.5	67	2.54
2015	FC2	6	F	C	F×C	2200	144	103	2.53
2015	FC3	3	F	C	F×C	1950	153.5	72	0.72
2015	FC4	2	F	C	F×C	750	140	51	1.53
2015	FC5	5	F	C	F×C	2250	170	96	3.53
2015	FC6	1	F	C	F×C	2700	160.5	100	2.73
2015	FS1	6	F	S	F×S	1000	145	50	2.08
2015	FS2	4	F	S	F×S	2500	167	95	3.43
2015	FS3	1	F	S	F×S	1300	148.5	52	1.50
2015	FS4	5	F	S	F×S	2300	155	91	3.16
2015	FS5	2	F	S	F×S	1900	175	84	3.70
2015	FS6	3	F	S	F×S	650	145	48	3.26
2015	BdB1	6	Rd	B	Rd×B	2100	142	80	2.92
2015	BdB2	3	Rd	B	Rd×B	2000	139.5	65	3.43
2015	BdB3	1	Rd	B	Rd×B	1500	110.5	46	3.41
2015	BdB4	5	Rd	B	Rd×B	2200	138.5	95	2.61
2015	BdB5	4	Rd	B	Rd×B	2400	156.5	99	4.21
2015	BdB6	2	Rd	B	Rd×B	1800	152	74	2.29
2015	BdBS1	6	Rd	BS	Rd×BS	1000	113	60	2.16
2015	BdBS2	2	Rd	BS	Rd×BS	1800	130.5	97	2.15
2015	BdBS3	5	Rd	BS	Rd×BS	1700	130	91	2.01
2015	BdBS4	3	Rd	BS	Rd-BS	1600	133	95	2.20
2015	BdBS5	4	Rd	BS	Rd×BS	2500	137	98	3.72
2015	BdBS6	1	Rd	BS	Rd×BS	2200	131.5	97	3.23
2015	BdC1	5	Rd	C	Rd×C	2400	142.5	96	3.53
2015	BdC2	3	Rd	C	Rd×C	1900	124.5	92	2.13
2015	BdC3	2	Rd	C	Rd×C	2600	133	83	1.88
2015	BdC4	6	Rd	C	Rd×C	1900	129	83	2.66
2015	BdC5	4	Rd	C	Rd×C	2300	150	98	3.99
2015	BdC6	1	Rd	C	Rd×C	1200	134.5	49	2.13
2015	BdS1	5	Rd	S	Rd×S	550	110.5	81	3.53
2015	BdS2	1	Rd	S	Rd×S	1900	135	97	2.69
2015	BdS3	3	Rd	S	Rd×S	1800	132	80	2.27
2015	BdS4	6	Rd	S	Rd×S	1300	133.5	78	3.67
2015	BdS5	4	Rd	S	Rd×S	2100	148	96	3.26
2015	BdS6	2	Rd	S	Rd×S	1800	125	74	3.17

Appendix 13: Tissue chemical analysis of Y-leaves sampled at panicle differentiation in 2014 (1)

Plant Tissues in 2014	**Plots_ID**	**Reps**	**PMs**	**AMDs**	**PMs×AMDs**	**Na**	**N**	**P**	**K**	**Mg**	**Ca**	**S**	**Fe**	**Mn**	**Zn**	**B**	**Cu**	**Al**
						%							**mg kg^{-1}**					
Leaves	FB1	1	F	B	F×B	0.46	3.21	0.2	1.64	0.25	0.33	0.25	98	106	29	22	10	3
Leaves	FB4	3	F	B	F×B	0.4	3.26	0.2	1.78	0.28	0.36	0.26	117	135	26	15	7	18
Leaves	FB6	2	F	B	F×B	0.2	2.79	0.18	1.81	0.22	0.34	0.23	83	125	26	13	7	9
Leaves	FBS2	1	F	BS	F×BS	0.35	2.9	0.15	2.09	0.23	0.38	0.24	98	125	27	14	8	21
Leaves	FBS3	2	F	BS	F×BS	0.24	2.42	0.20	2.14	0.20	0.34	0.23	80	135	27	12	7	6
Leaves	FBS5	3	F	BS	F×BS	0.14	2.32	0.19	2.09	0.19	0.33	0.20	82	108	22	12	7	2
Leaves	FC1	3	F	C	F×C	0.53	3.04	0.17	1.81	0.26	0.36	0.26	102	95	28	14	7	1
Leaves	FC2	2	F	C	F×C	0.15	2.69	0.16	2.19	0.19	0.36	0.23	80	127	26	11	8	7
Leaves	FC4	1	F	C	F×C	0.35	2.91	0.18	1.80	0.22	0.35	0.22	94	111	28	11	8	8
Leaves	FS4	2	F	S	F×S	0.28	2.70	0.14	1.85	0.23	0.37	0.23	84	110	22	14	8	19
Leaves	FS5	3	F	S	F×S	0.27	2.83	0.17	1.97	0.22	0.37	0.25	86	134	26	18	7	9
Leaves	FS6	1	F	S	F×S	0.48	3.41	0.21	1.56	0.27	0.30	0.25	103	106	25	15	7	5
Leaves	RdB1	1	R	B	R×B	0.30	3.02	0.16	1.79	0.22	0.33	0.24	98	120	23	12	7	1
Leaves	RdB2	3	R	B	R×B	0.37	2.68	0.12	1.86	0.21	0.36	0.20	107	109	20	10	8	5
Leaves	RdB3	2	R	B	R×B	0.57	2.89	0.12	1.34	0.24	0.36	0.25	111	190	21	15	7	3
Leaves	RdBS1	2	R	BS	R×BS	0.44	3.15	0.14	1.71	0.23	0.41	0.23	102	94	22	15	8	2
Leaves	RdBS3	1	R	BS	R×BS	0.45	2.91	0.11	1.65	0.23	0.38	0.23	114	105	22	13	6	6
Leaves	RdBS5	3	R	BS	R×BS	0.24	2.92	0.13	1.98	0.19	0.36	0.23	87	132	20	13	7	1
Leaves	RdC2	3	R	C	R×C	0.46	3.55	0.12	1.31	0.20	0.30	0.25	111	100	26	16	7	7
Leaves	RdC3	2	R	C	R×C	0.57	3.19	0.11	1.47	0.23	0.38	0.25	148	85	23	17	7	1
Leaves	RdC4	1	R	C	R×C	0.24	2.76	0.13	1.88	0.19	0.32	0.20	83	92	23	12	8	9
Leaves	RdS3	1	R	S	R×S	0.48	2.88	0.10	1.45	0.23	0.39	0.25	107	106	23	15	7	22
Leaves	RdS4	3	R	S	R×S	0.26	3.31	0.12	1.93	0.21	0.44	0.22	103	91	22	13	8	14
Leaves	RdS6	2	R	S	R×S	0.32	2.76	0.13	1.63	0.21	0.36	0.21	98	102	23	13	8	1

Appendix 14: Tissue chemical analysis of Y-leaves sampled at panicle differentiation in 2014 (2)

Plant Tissues in 2014	Plots_ID	Reps	PMs	AMDs	PMs×AMDs	N/S	N/K	P/S	P/Zn	K/Mg	K/Mn	Ca/b	Fe/Mn
						Ratio							
Leaves	FB1	1	F	B	F×B	12.8	2	0.8	69	6.6	154.7	150	0.9
Leaves	FB4	3	F	B	F×B	12.5	1.8	0.8	76.9	6.4	131.9	240	0.9
Leaves	FB6	2	F	B	F×B	12.1	1.5	0.8	69.2	8.2	144.8	261.5	0.7
Leaves	FBS2	1	F	BS	F×BS	12.1	1.4	0.6	55.6	9.1	167.2	271.4	0.8
Leaves	FBS3	2	F	BS	F×BS	10.5	1.1	0.9	74.1	10.7	158.5	283.3	0.6
Leaves	FBS5	3	F	BS	F×BS	11.6	1.1	1.0	86.4	11.0	193.5	275.0	0.8
Leaves	FC1	3	F	C	F×C	11.7	1.7	0.7	60.7	7.0	190.5	257.1	1.1
Leaves	FC2	2	F	C	F×C	11.7	1.2	0.7	61.5	11.5	172.4	327.3	0.6
Leaves	FC4	1	F	C	F×C	13.2	1.6	0.8	64.3	8.2	162.2	318.2	0.8
Leaves	FS4	2	F	S	F×S	11.7	1.5	0.6	63.6	8.0	168.2	264.3	0.8
Leaves	FS5	3	F	S	F×S	11.3	1.4	0.7	65.4	9.0	147.0	205.6	0.6
Leaves	FS6	1	F	S	F×S	13.6	2.2	0.8	84.0	5.8	147.2	200.0	1.0
Leaves	RdB1	1	R	B	R×B	12.6	1.7	0.7	69.6	8.1	149.2	275.0	0.8
Leaves	RdB2	3	R	B	R×B	13.4	1.4	0.6	60.0	8.9	170.6	360.0	1.0
Leaves	RdB3	2	R	B	R×B	11.6	2.2	0.5	57.1	5.6	70.5	240.0	0.6
Leaves	RdBS1	2	R	BS	R×BS	13.7	1.8	0.6	63.6	7.4	181.9	273.3	1.1
Leaves	RdBS3	1	R	BS	R×BS	12.7	1.8	0.5	50	7.2	157.1	292.3	1.1
Leaves	RdBS5	3	R	BS	R×BS	12.7	1.5	0.6	65.0	10.4	150.0	276.9	0.7
Leaves	RdC2	3	R	C	R×C	14.2	2.7	0.5	46.2	6.6	131.0	187.5	1.1
Leaves	RdC3	2	R	C	R×C	12.8	2.2	0.4	47.8	6.4	172.9	223.5	1.7
Leaves	RdC4	1	R	C	R×C	13.8	1.5	0.7	56.5	9.9	204.3	266.7	0.9
Leaves	RdS3	1	R	S	R×S	11.5	2.0	0.4	43.5	6.3	136.8	260.0	1.0
Leaves	RdS4	3	R	S	R×S	15.0	1.7	0.5	54.5	9.2	212.1	338.5	1.1
Leaves	RdS6	2	R	S	R×S	13.1	1.7	0.6	56.5	7.8	159.8	276.9	1.0

Appendix 15: Tissue chemical analysis of grains sampled at harvest in 2014 (1)

Plant Tissues in 2014	**Plots_ID**	**Reps**	**PMs**	**AMDs**	**PMs×AMDs**	**Na**	**N**	**P**	**K**	**Mg**	**Ca**	**S**	**Fe**	**Mn**	**Zn**	**B**	**Cu**	**Al**
						%							**mg kg^{-1}**					
Grains	FB1	1	F	B	F×B	0.07	8.93	0.13	0.25	0.28	0.11	1.25	22	25	3	0.03	24	7
Grains	FB4	3	F	B	F×B	0.04	3.50	0.13	0.26	0.24	0.11	1.14	29	22	2	0.02	13	9
Grains	FB6	2	F	B	F×B	0.05	4.22	0.12	0.30	0.27	0.13	1.24	27	27	2	0.02	18	6
Grains	FBS2	1	F	BS	F×BS	0.11	5.66	0.16	0.30	0.36	0.12	1.31	42	26	4	0.03	38	10
Grains	FBS3	2	F	BS	F×BS	0.04	4.62	0.12	0.26	0.23	0.11	1.23	24	24	3	0.02	16	7
Grains	FBS5	3	F	BS	F×BS	0.05	2.92	0.12	0.32	0.27	0.14	1.17	28	29	2	0.02	16	6
Grains	FC1	3	F	C	F×C	0.05	2.96	0.13	0.24	0.23	0.10	1.27	20	30	2	0.02	21	7
Grains	FC2	2	F	C	F×C	0.05	5.30	0.13	0.28	0.25	0.12	1.23	33	26	2	0.02	19	6
Grains	FC4	1	F	C	F×C	0.05	4.03	0.12	0.24	0.22	0.10	1.23	22	26	1	0.02	19	7
Grains	FS4	2	F	S	F×S	0.06	3.90	0.13	0.24	0.24	0.11	1.21	24	25	2	0.03	21	7
Grains	FS5	3	F	S	F×S	0.05	4.78	0.11	0.28	0.24	0.12	1.22	27	28	2	0.02	12	6
Grains	FS6	1	F	S	F×S	0.05	4.17	0.11	0.25	0.22	0.10	1.08	22	22	1	0.02	14	5
Grains	RdB1	1	R	B	R×B	0.05	5.56	0.13	0.26	0.24	0.12	1.27	19	24	2	0.03	21	6
Grains	RdB2	3	R	B	R×B	0.05	3.92	0.12	0.22	0.22	0.10	1.38	14	23	2	0.04	20	6
Grains	RdB3	2	R	B	R×B	0.04	1.98	0.13	0.23	0.20	0.10	1.37	16	23	1	0.05	17	5
Grains	RdBS1	2	R	BS	R×BS	0.04	4.55	0.11	0.26	0.25	0.12	1.32	16	23	2	0.02	15	6
Grains	RdBS3	1	R	BS	R×BS	0.05	2.11	0.12	0.26	0.23	0.11	1.26	17	22	2	0.03	21	6
Grains	RdBS5	3	R	BS	R×BS	0.05	5.56	0.12	0.24	0.23	0.11	1.20	16	23	1	0.03	24	7
Grains	RdC2	3	R	C	R×C	0.05	10.29	0.13	0.18	0.20	0.08	1.78	15	22	2	0.05	19	6
Grains	RdC3	2	R	C	R×C	0.04	2.04	0.13	0.20	0.20	0.09	1.32	19	21	1	0.03	15	5
Grains	RdC4	1	R	C	R×C	0.12	6.64	0.17	0.25	0.37	0.11	1.44	19	21	3	0.04	43	9
Grains	RdS3	1	R	S	R×S	0.04	1.11	0.13	0.18	0.19	0.09	1.46	37	27	1	0.03	22	5
Grains	RdS4	3	R	S	R×S	0.05	5.91	0.12	0.23	0.22	0.11	1.34	16	22	1	0.03	13	5
Grains	RdS6	2	R	S	R×S	0.04	3.97	0.13	0.19	0.18	0.09	1.35	19	25	3	0.02	22	6

Appendix 16: Tissue chemical analysis of grains sampled at harvest in 2014 (2)

Plant Tissues in 2014	Plots_ID	Reps	PMs	AMDs	PMs×AMDs	N/S	N/K	P/S	P/Zn	K/Mg	K/Mn	Ca/b	Fe/Mn
						Ratio							
Grains	FB1	1	F	B	F×B	1	9.6	4.5	1.9	100.0	2.5	127.3	233.3
Grains	FB4	3	F	B	F×B	6	8.8	4.8	2.0	118.2	2.2	82.8	200.0
Grains	FB6	2	F	B	F×B	1	10.3	4.6	2.5	111.1	2.1	100.0	250.0
Grains	FBS2	1	F	BS	F×BS	7	8.2	3.6	1.9	115.4	3.0	85.7	275.0
Grains	FBS3	2	F	BS	F×BS	1	10.3	5.3	2.2	108.3	2.1	95.8	133.3
Grains	FBS5	3	F	BS	F×BS	1	9.8	4.3	2.7	110.3	1.9	96.4	250.0
Grains	FC1	3	F	C	F×C	10	9.8	5.5	1.8	80.0	2.3	115.0	250.0
Grains	FC2	2	F	C	F×C	21	9.5	4.9	2.2	107.7	2.1	75.8	250.0
Grains	FC4	1	F	C	F×C	8	10.3	5.6	2.0	92.3	2.2	100.0	500.0
Grains	FS4	2	F	S	F×S	1	9.3	5.0	1.8	96.0	2.2	100.0	300.0
Grains	FS5	3	F	S	F×S	1	11.1	5.1	2.5	100.0	2.0	88.9	250.0
Grains	FS6	1	F	S	F×S	1	9.8	4.9	2.3	113.6	2.2	100.0	500.0
Grains	RdB1	1	R	B	R×B	3	9.8	5.3	2.0	108.3	2.0	126.3	250.0
Grains	RdB2	3	R	B	R×B	1	11.5	6.3	1.8	95.7	2.2	157.1	250.0
Grains	RdB3	2	R	B	R×B	4	10.5	6.9	1.8	100.0	2.0	125.0	400.0
Grains	RdBS1	2	R	BS	R×BS	4	12.0	5.3	2.4	113.0	2.1	156.3	200.0
Grains	RdBS3	1	R	BS	R×BS	1	10.5	5.5	2.2	118.2	2.1	135.3	250.0
Grains	RdBS5	3	R	BS	R×BS	16	10.0	5.2	2.0	104.3	2.1	143.8	500.0
Grains	RdC2	3	R	C	R×C	1	13.7	8.9	1.4	81.8	2.5	133.3	250.0
Grains	RdC3	2	R	C	R×C	1	10.2	6.6	1.5	95.2	2.2	105.3	400.0
Grains	RdC4	1	R	C	R×C	7	8.5	3.9	1.5	119.0	3.4	194.7	400.0
Grains	RdS3	1	R	S	R×S	14	11.2	7.7	1.4	66.7	2.1	51.4	400.0
Grains	RdS4	3	R	S	R×S	3	11.2	6.1	1.9	104.5	2.0	137.5	500.0
Grains	RdS6	2	R	S	R×S	1	10.4	7.5	1.5	76.0	2.0	94.7	133.3

Appendix 17: Water EC, pH, and Height of shallow and deep piezometers in the Upper Site in 2014 (1)

Locations	**Sites**	**Weekly Measurements**	**Weeks**	**Piezometers**	**EC ($dS\ m^{-1}$)**	**pH**	**Water Height (cm)**
P7	Upper	8/2/2014	1	Shallow	.	.	-35.50
P7	Upper	8/9/2014	2	Shallow	.	.	-35.50
P7	Upper	8/16/2014	3	Shallow	0.68	6.20	25.00
P7	Upper	8/23/2014	4	Shallow	0.37	6.40	22.00
P7	Upper	9/1/2014	5	Shallow	0.49	6.20	12.00
P7	Upper	9/8/2014	6	Shallow	0.54	6.90	18.50
P7	Upper	9/15/2014	7	Shallow	0.63	7.00	22.50
P7	Upper	9/22/2014	8	Shallow	0.51	7.30	24.50
P7	Upper	9/29/2014	9	Shallow	0.30	7.40	11.50
P7	Upper	10/7/2014	10	Shallow	0.38	7.50	18.50
P7	Upper	10/13/2014	11	Shallow	0.45	8.00	14.50
P7	Upper	10/20/2014	12	Shallow	0.21	5.20	15.00
P7	Upper	10/27/2014	13	Shallow	0.33	6.90	16.00
P7	Upper	11/3/2014	14	Shallow	0.24	7.10	12.50
P7	Upper	11/10/2014	15	Shallow	0.21	6.60	11.50
P7	Upper	11/17/2014	16	Shallow	0.19	5.30	9.50
P7	Upper	11/24/2014	17	Shallow	0.20	4.20	5.50
P8	Upper	8/2/2014	1	Shallow	.	.	-33.00
P8	Upper	8/9/2014	2	Shallow	.	.	-33.00
P8	Upper	8/16/2014	3	Shallow	0.59	5.50	8.50
P8	Upper	8/23/2014	4	Shallow	0.46	4.00	8.50
P8	Upper	9/1/2014	5	Shallow	0.48	4.00	2.00
P8	Upper	9/8/2014	6	Shallow	0.54	4.60	5.00
P8	Upper	9/15/2014	7	Shallow	0.51	4.40	9.00
P8	Upper	9/22/2014	8	Shallow	0.46	4.50	8.00
P8	Upper	9/29/2014	9	Shallow	0.27	5.10	6.00
P8	Upper	10/7/2014	10	Shallow	0.38	4.80	4.00
P8	Upper	10/13/2014	11	Shallow	0.36	5.60	1.50
P8	Upper	10/20/2014	12	Shallow	0.21	3.80	1.00
P8	Upper	10/27/2014	13	Shallow	0.23	4.10	2.50
P8	Upper	11/3/2014	14	Shallow	0.21	4.90	1.00
P8	Upper	11/10/2014	15	Shallow	0.19	5.00	2.50
P8	Upper	11/17/2014	16	Shallow	0.19	4.10	0.00
P8	Upper	11/24/2014	17	Shallow	0.16	4.00	-5.00

Appendix 17: Water EC, pH, and Height of shallow and deep piezometers in the Upper Site in 2014 (2)

Locations	Sites	Weekly Measurements	Weeks	Piezometers	EC ($dS\ m^{-1}$)	pH	Water Height (cm)
P9	Upper	8/2/2014	1	Shallow	.	.	-29.00
P9	Upper	8/9/2014	2	Shallow	.	.	-29.00
P9	Upper	8/16/2014	3	Shallow	0.97	5.60	11.00
P9	Upper	8/23/2014	4	Shallow	0.67	5.20	9.00
P9	Upper	9/1/2014	5	Shallow	0.74	5.60	14.00
P9	Upper	9/8/2014	6	Shallow	0.82	6.20	14.50
P9	Upper	9/15/2014	7	Shallow	0.66	6.00	20.00
P9	Upper	9/22/2014	8	Shallow	0.73	7.00	16.00
P9	Upper	9/29/2014	9	Shallow	0.51	8.30	15.00
P9	Upper	10/7/2014	10	Shallow	0.60	7.00	18.00
P9	Upper	10/13/2014	11	Shallow	0.76	7.80	13.00
P9	Upper	10/20/2014	12	Shallow	0.29	6.40	15.00
P9	Upper	10/27/2014	13	Shallow	0.43	6.80	20.00
P9	Upper	11/3/2014	14	Shallow	0.27	5.80	15.00
P9	Upper	11/10/2014	15	Shallow	0.23	5.50	15.50
P9	Upper	11/17/2014	16	Shallow	0.18	4.70	13.00
P9	Upper	11/24/2014	17	Shallow	0.19	4.50	12.00
P7	Upper	8/2/2014	1	Deep	.	.	-116.00
P7	Upper	8/9/2014	2	Deep	0.67	6.10	-100.50
P7	Upper	8/16/2014	3	Deep	0.58	6.50	23.00
P7	Upper	8/23/2014	4	Deep	0.39	6.60	29.00
P7	Upper	9/1/2014	5	Deep	0.42	6.50	16.00
P7	Upper	9/8/2014	6	Deep	0.59	7.10	24.00
P7	Upper	9/15/2014	7	Deep	0.69	8.00	29.00
P7	Upper	9/22/2014	8	Deep	0.76	7.40	22.00
P7	Upper	9/29/2014	9	Deep	0.47	8.00	27.00
P7	Upper	10/7/2014	10	Deep	0.48	7.50	19.00
P7	Upper	10/13/2014	11	Deep	0.46	7.20	12.00
P7	Upper	10/20/2014	12	Deep	0.25	6.20	17.00
P7	Upper	10/27/2014	13	Deep	0.34	6.80	18.00
P7	Upper	11/3/2014	14	Deep	0.24	7.00	13.00
P7	Upper	11/10/2014	15	Deep	0.21	6.70	12.00
P7	Upper	11/17/2014	16	Deep	0.18	5.50	8.00
P7	Upper	11/24/2014	17	Deep	0.19	4.90	5.00

Appendix 18: Water EC, pH, and Height of shallow and deep piezometers in the Upper Site in 2014 (3)

Locations	Sites	Weekly Measurements	Weeks	Piezometers	EC (dS m^{-1})	pH	Water Height (cm)
P8	Upper	8/9/2014	2	Deep	0.45	3.80	-106.50
P8	Upper	8/16/2014	3	Deep	0.51	3.30	16.00
P8	Upper	8/23/2014	4	Deep	0.48	3.30	27.00
P8	Upper	9/1/2014	5	Deep	0.51	3.30	8.00
P8	Upper	9/8/2014	6	Deep	0.58	3.70	12.00
P8	Upper	9/15/2014	7	Deep	0.63	4.20	17.00
P8	Upper	9/22/2014	8	Deep	0.42	4.40	18.00
P8	Upper	9/29/2014	9	Deep	0.27	4.90	16.00
P8	Upper	10/7/2014	10	Deep	0.41	4.50	12.00
P8	Upper	10/13/2014	11	Deep	0.33	4.70	10.00
P8	Upper	10/20/2014	12	Deep	0.21	3.70	10.00
P8	Upper	10/27/2014	13	Deep	0.22	3.80	12.00
P8	Upper	11/3/2014	14	Deep	0.19	4.50	-2.00
P8	Upper	11/10/2014	15	Deep	0.18	4.60	13.00
P8	Upper	11/17/2014	16	Deep	0.18	3.70	9.00
P8	Upper	11/24/2014	17	Deep	0.16	3.30	3.00
P9	Upper	8/2/2014	1	Deep	0.21	6.20	-51.00
P9	Upper	8/9/2014	2	Deep	1.20	6.60	-77.50
P9	Upper	8/16/2014	3	Deep	0.83	6.00	32.00
P9	Upper	8/23/2014	4	Deep	0.70	5.90	37.00
P9	Upper	9/1/2014	5	Deep	0.71	6.10	30.00
P9	Upper	9/8/2014	6	Deep	0.86	6.50	37.00
P9	Upper	9/15/2014	7	Deep	0.76	8.00	32.00
P9	Upper	9/22/2014	8	Deep	0.71	7.20	34.00
P9	Upper	9/29/2014	9	Deep	0.50	7.60	29.00
P9	Upper	10/7/2014	10	Deep	0.60	7.20	33.00
P9	Upper	10/13/2014	11	Deep	0.51	6.70	26.00
P9	Upper	10/20/2014	12	Deep	0.31	6.40	25.00
P9	Upper	10/27/2014	13	Deep	0.44	6.50	34.00
P9	Upper	11/3/2014	14	Deep	0.25	5.20	31.00
P9	Upper	11/10/2014	15	Deep	0.22	5.50	30.00
P9	Upper	11/17/2014	16	Deep	0.18	4.50	29.00
P9	Upper	11/24/2014	17	Deep	0.19	4.90	25.00

Appendix 19: Water EC, pH, and Height of shallow and deep piezometers in the Middle Site in 2014 (4)

Locations	Sites	Weekly Measurements	Weeks	Piezometers	EC ($dS\ m^{-1}$)	pH	Water Height (cm)
P16	Middle	8/9/2014	2	Shallow	.	.	-35.50
P16	Middle	8/16/2014	3	Shallow	6.95	7.30	14.50
P16	Middle	8/23/2014	4	Shallow	9.06	7.00	14.50
P16	Middle	9/1/2014	5	Shallow	10.09	6.00	12.50
P16	Middle	9/8/2014	6	Shallow	10.30	5.80	14.50
P16	Middle	9/15/2014	7	Shallow	9.83	5.90	15.50
P16	Middle	9/22/2014	8	Shallow	10.08	5.80	21.50
P16	Middle	9/29/2014	9	Shallow	7.12	8.00	18.50
P16	Middle	10/7/2014	10	Shallow	7.57	7.70	15.00
P16	Middle	10/13/2014	11	Shallow	3.55	7.30	15.50
P16	Middle	10/20/2014	12	Shallow	1.93	6.50	4.50
P16	Middle	10/27/2014	13	Shallow	1.22	6.60	0.00
P16	Middle	11/3/2014	14	Shallow	0.79	6.70	16.50
P16	Middle	11/10/2014	15	Shallow	0.85	6.90	13.00
P16	Middle	11/17/2014	16	Shallow	0.58	6.90	7.50
P16	Middle	11/24/2014	17	Shallow	1.12	6.70	4.00
P17	Middle	8/2/2014	1	Shallow	.	.	-41.00
P17	Middle	8/9/2014	2	Shallow	.	.	-41.00
P17	Middle	8/16/2014	3	Shallow	8.23	7.00	21.00
P17	Middle	8/23/2014	4	Shallow	8.69	6.90	17.00
P17	Middle	9/1/2014	5	Shallow	9.12	6.70	11.00
P17	Middle	9/8/2014	6	Shallow	9.22	6.80	10.00
P17	Middle	9/15/2014	7	Shallow	8.65	7.30	11.00
P17	Middle	9/22/2014	8	Shallow	9.28	7.10	15.50
P17	Middle	9/29/2014	9	Shallow	6.43	8.50	15.00
P17	Middle	10/7/2014	10	Shallow	7.53	6.60	11.00
P17	Middle	10/13/2014	11	Shallow	3.28	6.50	-6.00
P17	Middle	10/20/2014	12	Shallow	2.06	6.60	12.00
P17	Middle	10/27/2014	13	Shallow	1.25	6.50	17.00
P17	Middle	11/3/2014	14	Shallow	0.83	6.70	14.00
P17	Middle	11/10/2014	15	Shallow	0.80	6.90	6.00
P17	Middle	11/17/2014	16	Shallow	0.51	6.70	-1.50
P17	Middle	11/24/2014	17	Shallow	1.03	6.50	-2.00

Appendix 20: Water EC, pH, and Height of shallow and deep piezometers in the Middle Site in 2014 (5)

Locations	Sites	Weekly Measurements	Weeks	Piezometers	EC (dS m^{-1})	pH	Water Height (cm)
P18	Middle	8/9/2014	2	Shallow	12.99	7.00	-14.00
P18	Middle	8/16/2014	3	Shallow	12.38	7.00	18.50
P18	Middle	8/23/2014	4	Shallow	11.91	6.50	16.50
P18	Middle	9/1/2014	5	Shallow	11.83	5.80	8.50
P18	Middle	9/8/2014	6	Shallow	11.50	4.10	6.50
P18	Middle	9/15/2014	7	Shallow	10.72	4.60	9.50
P18	Middle	9/22/2014	8	Shallow	8.59	5.00	9.50
P18	Middle	9/29/2014	9	Shallow	6.96	5.10	9.00
P18	Middle	10/7/2014	10	Shallow	6.00	5.60	6.50
P18	Middle	10/13/2014	11	Shallow	1.95	6.80	5.00
P18	Middle	10/20/2014	12	Shallow	1.58	3.20	5.00
P18	Middle	10/27/2014	13	Shallow	0.74	6.70	6.50
P18	Middle	11/3/2014	14	Shallow	0.52	7.10	5.50
P18	Middle	11/10/2014	15	Shallow	0.52	7.30	3.50
P18	Middle	11/17/2014	16	Shallow	0.33	7.00	2.50
P18	Middle	11/24/2014	17	Shallow	0.49	6.80	1.50
P16	Middle	8/2/2014	1	Deep	9.70	6.50	-87.00
P16	Middle	8/9/2014	2	Deep	11.50	6.60	-31.00
P16	Middle	8/16/2014	3	Deep	11.50	6.70	7.00
P16	Middle	8/23/2014	4	Deep	11.36	6.90	18.00
P16	Middle	9/1/2014	5	Deep	11.12	7.00	8.00
P16	Middle	9/8/2014	6	Deep	10.97	7.10	27.00
P16	Middle	9/15/2014	7	Deep	10.22	7.70	11.00
P16	Middle	9/22/2014	8	Deep	10.24	7.30	17.00
P16	Middle	9/29/2014	9	Deep	7.52	8.40	15.00
P16	Middle	10/7/2014	10	Deep	8.44	7.30	11.00
P16	Middle	10/13/2014	11	Deep	3.74	6.40	13.00
P16	Middle	10/20/2014	12	Deep	2.21	5.80	12.00
P16	Middle	10/27/2014	13	Deep	1.54	6.50	13.00
P16	Middle	11/3/2014	14	Deep	0.85	6.50	12.00
P16	Middle	11/10/2014	15	Deep	0.89	6.70	9.00
P16	Middle	11/17/2014	16	Deep	0.61	6.80	2.00
P16	Middle	11/24/2014	17	Deep	1.30	6.30	-5.00

Appendix 21: Water EC, pH, and Height of shallow and deep piezometers in the Middle Site in 2014 (5)

Locations	Sites	Weekly Measurements	Weeks	Piezometers	EC (dS m^{-1})	pH	Water Height (cm)
P17	Middle	8/9/2014	2	Deep	12.70	6.70	-14.00
P17	Middle	8/16/2014	3	Deep	12.44	6.50	-80.50
P17	Middle	8/23/2014	4	Deep	12.31	6.50	23.00
P17	Middle	9/1/2014	5	Deep	11.95	6.70	14.00
P17	Middle	9/8/2014	6	Deep	11.75	7.00	16.00
P17	Middle	9/15/2014	7	Deep	11.13	6.90	16.00
P17	Middle	9/22/2014	8	Deep	11.23	7.50	18.00
P17	Middle	9/29/2014	9	Deep	9.12	8.00	19.00
P17	Middle	10/7/2014	10	Deep	9.71	7.50	16.00
P17	Middle	10/13/2014	11	Deep	5.28	6.10	16.00
P17	Middle	10/20/2014	12	Deep	3.02	6.30	16.00
P17	Middle	10/27/2014	13	Deep	1.90	6.40	21.00
P17	Middle	11/3/2014	14	Deep	1.06	6.60	19.00
P17	Middle	11/10/2014	15	Deep	0.94	6.70	13.00
P17	Middle	11/17/2014	16	Deep	0.58	6.50	8.00
P17	Middle	11/24/2014	17	Deep	1.28	6.40	3.00
P18	Middle	8/2/2014	1	Deep	10.64	5.80	-47.00
P18	Middle	8/9/2014	2	Deep	11.73	5.30	-7.00
P18	Middle	8/16/2014	3	Deep	12.10	6.50	24.00
P18	Middle	8/23/2014	4	Deep	12.33	4.80	30.00
P18	Middle	9/1/2014	5	Deep	12.21	2.90	16.00
P18	Middle	9/8/2014	6	Deep	12.00	3.20	18.00
P18	Middle	9/15/2014	7	Deep	11.68	3.60	18.00
P18	Middle	9/22/2014	8	Deep	11.53	3.50	16.00
P18	Middle	9/29/2014	9	Deep	9.21	3.90	18.00
P18	Middle	10/7/2014	10	Deep	9.92	4.30	15.00
P18	Middle	10/13/2014	11	Deep	7.56	4.40	15.00
P18	Middle	10/20/2014	12	Deep	5.02	6.00	15.00
P18	Middle	10/27/2014	13	Deep	3.54	6.00	17.00
P18	Middle	11/3/2014	14	Deep	1.76	6.30	16.00
P18	Middle	11/10/2014	15	Deep	0.99	6.30	14.00
P18	Middle	11/17/2014	16	Deep	0.91	6.20	10.00
P18	Middle	11/24/2014	17	Deep	2.22	4.30	10.00

Appendix 22: Water EC, pH, and Height of shallow and deep piezometers in the Lower Site in 2014 (6)

Locations	Sites	Weekly Measurements	Weeks	Piezometers	EC (dS m^{-1})	pH	Water Height (cm)
P31	Lower	8/9/2014	2	Shallow	10.54	6.80	-18.00
P31	Lower	8/16/2014	3	Shallow	10.61	6.80	6.00
P31	Lower	8/23/2014	4	Shallow	12.18	6.00	5.00
P31	Lower	9/1/2014	5	Shallow	11.20	5.70	-5.00
P31	Lower	9/8/2014	6	Shallow	8.64	6.80	10.00
P31	Lower	9/15/2014	7	Shallow	9.50	7.70	6.50
P31	Lower	9/22/2014	8	Shallow	10.65	7.50	11.00
P31	Lower	9/29/2014	9	Shallow	6.14	8.60	6.50
P31	Lower	10/7/2014	10	Shallow	7.48	7.50	-4.00
P31	Lower	10/13/2014	11	Shallow	2.88	6.90	-2.50
P31	Lower	10/20/2014	12	Shallow	2.51	5.80	-3.00
P31	Lower	10/27/2014	13	Shallow	0.66	6.70	-4.00
P31	Lower	11/3/2014	14	Shallow	0.52	7.00	3.00
P31	Lower	11/10/2014	15	Shallow	0.52	6.80	2.00
P31	Lower	11/17/2014	16	Shallow	0.39	6.90	-5.50
P31	Lower	11/24/2014	17	Shallow	0.28	6.70	-25.00
P32	Lower	8/2/2014	1	Shallow	13.33	6.70	-7.50
P32	Lower	8/9/2014	2	Shallow	12.24	6.60	3.00
P32	Lower	8/16/2014	3	Shallow	13.27	5.70	20.00
P32	Lower	8/23/2014	4	Shallow	13.60	3.70	10.00
P32	Lower	9/1/2014	5	Shallow	13.13	3.70	-0.50
P32	Lower	9/8/2014	6	Shallow	12.48	6.10	25.00
P32	Lower	9/15/2014	7	Shallow	8.78	8.00	25.00
P32	Lower	9/22/2014	8	Shallow	10.13	7.70	14.50
P32	Lower	9/29/2014	9	Shallow	9.49	5.60	8.50
P32	Lower	10/7/2014	10	Shallow	9.01	7.50	2.00
P32	Lower	10/13/2014	11	Shallow	3.63	6.40	4.00
P32	Lower	10/20/2014	12	Shallow	4.53	5.90	4.00
P32	Lower	10/27/2014	13	Shallow	1.24	6.00	3.50
P32	Lower	11/3/2014	14	Shallow	0.88	6.50	3.50
P32	Lower	11/10/2014	15	Shallow	0.52	6.80	6.00
P32	Lower	11/17/2014	16	Shallow	0.36	6.50	0.00
P32	Lower	11/24/2014	17	Shallow	0.29	6.40	-15.50

Appendix 23: Water EC, pH, and Height of shallow and deep piezometers in the Lower Site in 2014 (7)

Locations	**Sites**	**Weekly Measurements**	**Weeks**	**Piezometers**	**EC ($dS\ m^{-1}$)**	**pH**	**Water Height (cm)**
P33	Lower	8/9/2014	2	Shallow	14.64	6.00	4.00
P33	Lower	8/16/2014	3	Shallow	14.21	6.20	30.00
P33	Lower	8/23/2014	4	Shallow	14.85	6.20	37.50
P33	Lower	9/1/2014	5	Shallow	14.10	5.80	3.00
P33	Lower	9/8/2014	6	Shallow	14.24	6.10	21.00
P33	Lower	9/15/2014	7	Shallow	14.10	6.20	20.00
P33	Lower	9/22/2014	8	Shallow	13.70	7.20	17.00
P33	Lower	9/29/2014	9	Shallow	11.98	7.80	12.00
P33	Lower	10/7/2014	10	Shallow	13.99	6.80	3.00
P33	Lower	10/13/2014	11	Shallow	11.04	6.00	-3.00
P33	Lower	10/20/2014	12	Shallow	11.05	5.20	2.00
P33	Lower	10/27/2014	13	Shallow	5.51	6.10	1.00
P33	Lower	11/3/2014	14	Shallow	3.54	6.00	-7.00
P33	Lower	11/10/2014	15	Shallow	3.20	5.90	-3.00
P33	Lower	11/17/2014	16	Shallow	2.10	5.70	-22.00
P33	Lower	11/24/2014	17	Shallow	.	.	-35.00
P31	Lower	8/2/2014	1	Deep	11.32	6.40	82.00
P31	Lower	8/9/2014	2	Deep	12.53	6.50	9.00
P31	Lower	8/16/2014	3	Deep	13.15	6.40	42.00
P31	Lower	8/23/2014	4	Deep	13.70	6.30	18.00
P31	Lower	9/1/2014	5	Deep	12.50	6.80	2.00
P31	Lower	9/8/2014	6	Deep	11.77	6.60	29.00
P31	Lower	9/15/2014	7	Deep	8.82	7.80	29.00
P31	Lower	9/22/2014	8	Deep	7.16	7.80	31.00
P31	Lower	9/29/2014	9	Deep	5.16	8.70	24.00
P31	Lower	10/7/2014	10	Deep	8.04	7.80	15.00
P31	Lower	10/13/2014	11	Deep	3.89	6.90	8.00
P31	Lower	10/20/2014	12	Deep	3.53	5.90	6.00
P31	Lower	10/27/2014	13	Deep	0.96	6.60	5.00
P31	Lower	11/3/2014	14	Deep	0.64	6.60	11.00
P31	Lower	11/10/2014	15	Deep	0.54	6.80	8.00
P31	Lower	11/17/2014	16	Deep	0.40	6.80	2.00
P31	Lower	11/24/2014	17	Deep	0.50	6.30	-18.00

Appendix 24: Water EC, pH, and Height of shallow and deep piezometers in the Lower Site in 2014 (8)

Locations	Sites	Weekly Measurements	Weeks	Piezometers	EC ($dS\ m^{-1}$)	pH	Water Height (cm)
P32	Lower	8/9/2014	2	Deep	12.87	6.00	22.00
P32	Lower	8/16/2014	3	Deep	13.25	6.30	30.00
P32	Lower	8/23/2014	4	Deep	13.63	6.10	11.00
P32	Lower	9/1/2014	5	Deep	13.27	6.00	1.00
P32	Lower	9/8/2014	6	Deep	11.24	6.30	31.00
P32	Lower	9/15/2014	7	Deep	9.72	7.80	35.00
P32	Lower	9/22/2014	8	Deep	11.13	7.50	26.00
P32	Lower	9/29/2014	9	Deep	10.06	7.10	18.00
P32	Lower	10/7/2014	10	Deep	11.29	7.30	7.00
P32	Lower	10/13/2014	11	Deep	6.35	6.40	11.00
P32	Lower	10/20/2014	12	Deep	6.56	5.60	0.00
P32	Lower	10/27/2014	13	Deep	1.45	6.70	0.00
P32	Lower	11/3/2014	14	Deep	1.02	6.40	0.00
P32	Lower	11/10/2014	15	Deep	0.75	6.40	3.00
P32	Lower	11/17/2014	16	Deep	0.53	6.20	-5.00
P32	Lower	11/24/2014	17	Deep	0.35	6.30	-11.00
P33	Lower	8/2/2014	1	Deep	12.12	6.50	-71.50
P33	Lower	8/9/2014	2	Deep	13.82	6.60	14.00
P33	Lower	8/16/2014	3	Deep	14.01	6.70	33.00
P33	Lower	8/23/2014	4	Deep	14.52	6.40	18.00
P33	Lower	9/1/2014	5	Deep	13.81	6.70	14.00
P33	Lower	9/8/2014	6	Deep	13.95	6.60	23.00
P33	Lower	9/15/2014	7	Deep	13.13	7.50	18.00
P33	Lower	9/22/2014	8	Deep	13.36	7.30	22.00
P33	Lower	9/29/2014	9	Deep	11.20	8.40	15.00
P33	Lower	10/7/2014	10	Deep	13.21	7.30	6.00
P33	Lower	10/13/2014	11	Deep	10.75	6.20	0.00
P33	Lower	10/20/2014	12	Deep	10.02	4.50	2.00
P33	Lower	10/27/2014	13	Deep	4.98	6.00	4.00
P33	Lower	11/3/2014	14	Deep	3.36	6.20	-6.00
P33	Lower	11/10/2014	15	Deep	2.88	6.30	-2.00
P33	Lower	11/17/2014	16	Deep	1.98	6.30	-21.00
P33	Lower	11/24/2014	17	Deep	5.40	5.80	-37.00

Appendix 25: Daily rainfall in 2009 rainy season in Djibelor, Ziguinchor/Senegal

2009	**May**	**June**	**July**	**August**	**September**	**October**	**November**
1			37		3		
2				5.5	37		
3				4			
4				8	13		
5			2	63	5		
6				2	7		
7		10		18			
8				1	3.5		
9			3		33		
10			4.5	0.5	16		
Décade 1-10	**0**	**10**	**46.5**	**102**	**117.5**	**0**	**0**
11			3	15	15		
12			28	42	0.5		
13				2		48	
14		6	28	7	3		
15		0.5		21	43		
16				20	40		
17					2	1.5	
18		45		6		1.2	
19			1	1			
20			7	32			
Décade 11-20	**0**	**51.5**	**67**	**146**	**103.5**	**50.7**	**0**
21			5	7			
22				1	7		
23			1		100.4		
24				30	22	12	
25		1		42			
26			6	1	4.3	7	
27			6				
28		T	55	2			
29			1	28	2.3		
30			4	4			
31			10	80			
Décade 21-30-31	**0**	**1**	**88**	**195**	**136**	**19**	**0**
Monthly	0	62.5	201.5	443	357	69.7	0
Season	0	62.5	264	707	1064	1133.7	1133.7
# Days/month	0	5	17	26	19	5	0

Appendix 26: Daily rainfall in 2010 rainy season in Djibelor, Ziguinchor/Senegal

2010	May	June	July	August	September	October	November
1				4	18	12	
2			39	30	18.5		
3			32	7.5	4		
4			25	11.5		15	
5				28	111		
6					119		
7			6	10	2		
8			12	3.5	2.5	5.5	
9							
10					15		
Décade 1-10	**0**	**0**	**114**	**94.5**	**290**	**32.5**	**0**
11			37		54	16	
12			5		1.5	9	
13			4	26	18	0.5	
14				4.5	T	0.5	
15			20	4	1	11	
16				11.5	1.5	13	
17				1.5	15	1	
18			11	20	83		
19			13		40	13	
20			32	9	38		
Décade 11-20	**0**	**0**	**122**	**76.5**	**252**	**64**	**0**
21			2	42		0.5	
22			6	1	18		
23		32			29		
24			7	3.2	9		
25		16	26	62	26		
26				2.5	18		
27			11	21			
28		12	8		56		
29		30	36				
30							
31			25	61			
Décade 21-30-31	**0**	**90**	**121**	**192.7**	**156**	**0.5**	**0**
Monthly	0	90	357	363.7	698	97	0
Season	0	90	447	810.7	1508.7	1605.7	1605.7
# Days/month	0	4	20	21	23	12	0

Appendix 27: Daily rainfall in 2011 rainy season in Djibelor, Ziguinchor/Senegal

2011	**May**	**June**	**July**	**August**	**September**	**October**	**November**
1			18	2.5	15	56	
2			44	24	8	16	
3				6	7.5		
4				0.5	9	2.5	
5			5				
6			10	100			
7							
8				155			
9						6	
10				22			
Décade 1-10	**0**	**0**	**77**	**310**	**39.5**	**80.5**	**0**
11					0.5		
12					30		
13			20				
14		1	1	100	1	3.5	
15				3.5	18		
16			9	4.5	2		
17		5	T	5	0.5	16	
18			1	24			
19			55	37	18		
20				14	3		
Décade 11-20	**0**	**6**	**86**	**188**	**73**	**19.5**	**0**
21		15		37			
22			2	12	10	1.5	
23					15		
24		15		6.5	2		
25				13	12		
26		35		21			
27				32			
28		2	9		0.5		
29			4	2.5	20		
30			21			1.5	
31				6			
Décade 21-30-31	**0**	**67**	**36**	**130**	**59.5**	**3**	**0**
Monthly	0	73	199	628	172	103	0
Season	0	73	272	900	1072	1175	1175
# Days/month	0	6	13	22	18	8	0

Appendix 28: Daily rainfall in 2012 rainy season in Djibelor, Ziguinchor/Senegal

2012	May	June	July	August	September	October	November
1			1	9	36		
2			21	5	17		
3			20		50	12	
4			4	55	13		
5				50	27	13	
6			38		17		
7			41	3	3	11	
8			1.5	20			
9			5		30		
10				1.5	12	7	
Décade 1-10	**0**	**0**	**131.5**	**143.5**	**205**	**43**	**0**
11			1.5	83	2	2	
12			33	6			
13				29	7	2	
14			37	3			
15			6	8			
16			15	41			
17			8.5	30	T	21	
18			33	40	5		
19			20	4.5	45		
20			36	18		0.5	
Décade 11-20	**0**	**0**	**190**	**262.5**	**59**	**25.5**	**0**
21			12		14	21	
22				47	20		
23		0.5	37	0.5	13	12	
24		10.5	10	0.5	T		
25		25		26	8		
26		10.5	30	20	14		
27		8	25	10	62		
28				4	14		
29		11	4				
30			3.5		2		
31			2.5	17		9	
Décade 21-30-31	**0**	**65.5**	**124**	**125**	**147**	**42**	**0**
Monthly	0	65.5	445.5	531	411	110.5	0
Season	0	65.5	511	1042	1453	1563.5	1563.5
# Days/month	0	6	25	25	21	11	0

Appendix 29: Daily rainfall in 2013 rainy season in Djibelor, Ziguinchor/Senegal

2013	May	June	July	August	September	October	November
1			20	25			12
2				87			
3			40	8	6	12	
4				2	10		
5				1.5		2.5	
6				9	27	24	
7			10	24	3		
8		10	5		23	1	
9			50	7		24	
10			10	32			
Décade 1-10	**0**	**10**	**135**	**196**	**69**	**64**	**12**
11		0.5		26	T	28	
12				90	18	3	
13			1	21		41	
14			3	0.5	33		
15				64	19		
16			3	11		26	
17			4.5				
18				22	37	11	
19				46	3		
20			28				
Décade 11-20	**0**	**0.5**	**39.5**	**280.5**	**110**	**109**	**0**
21			27	40			
22			37	15	56	16	
23							
24				15			
25			4.5				
26			57	21	37		
27			40	3	22	0.2	
28							
29		6	3	40		18	
30			2	15			
31			59				
Décade 21-30-31	**0**	**6**	**229.5**	**149**	**115**	**34.2**	**0**
Monthly	0	16.5	404	625	294	206.7	12
Season	0	16.5	420.5	1045.5	1339.5	1546.2	1558.2
# Days/month	0	3	19	24	13	13	1

Appendix 30: Daily rainfall in 2014 rainy season in Djibelor, Ziguinchor/Senegal

2014	**May**	**June**	**July**	**August**	**September**	**October**	**November**
1				7		11	
2		25	0.5				
3			22	45	35		
4			4	9		9	
5			36	8			
6		1.9		7			
7					42	10	
8				4	3	8	
9			1.5	10	53	4	
10			11	7	10		
Décade 1-10	**0**	**27**	**75**	**97**	**143**	**42**	**0**
11		3	23	100	20		
12				4			
13				51	25		
14		3.5		46	15	10	
15		21	0.5	12	60		
16			0.5	7	15	5	
17				33	3		
18				88	25		
19			5	3	40		
20		2			3	5	
Décade 11-20	**0**	**29.5**	**29**	**344**	**206**	**20**	**0**
21				46	17		
22				60			
23			11	12			
24		8			12		
25				25	37	7	
26			22		1	19	
27				40			
28				0.5			
29							
30			27	2			
31			6				
Décade 21-30-31	**0**	**8**	**66**	**185.5**	**67**	**26**	**0**
Monthly	0	64.4	170	626.5	416	88	0
Season	0	64.4	234.4	860.9	1276.9	1364.9	1364.9
# Days/month	0	7	14	24	18	10	0

Appendix 31: Daily rainfall in 2015 rainy season in Djibelor, Ziguinchor/Senegal

2015	May	June	July	August	September	October	November
1				27	8	34	19
2				2	2.5		12
3				36	40	10	
4				25			
5						11	
6			16		98	6	
7			3		19		
8			75				
9			11	2.5	29		
10					1.5		
Décade 1-10	**0**	**0**	**105**	**93**	**198**	**61**	**31**
11		0.5	19	2			
12			4	22		51	16
13				2	25	33	
14			16	25			
15				1	14	1	
16		12		40	3	8	
17				32			
18			27	14		6	
19				1.5	17		
20		0.5		28			
Décade 11-20	**0**	**13**	**66**	**167.5**	**59**	**99**	**16**
21						7	
22		3		4			
23				41	74	39	
24			6		12	27	
25			95	21			
26			23				
27			44		28		
28			4	9	10		
29		2	0.5	10			
30		0.5	3.5	5			
31			66				
Décade 21-30-31	**0**	**5.5**	**242**	**90**	**124**	**73**	**0**
Monthly	0	18.5	413	350	381	233	47
Season	0	18.5	431.5	781.5	1162.5	1395.5	1442.5
# Days/month	0	6	16	21	15	12	3