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The effect of sulfur fertilization on rice yields and nitrogen use efficiency in a floodplain ecosystem of northern Ghana

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ABSTRACT

River floodplains are potential land resources to extend rice cultivation areas, most of which are not currently used for farming in West Africa. The major constraints that limit expansion of crop production in floodplain areas include difficulties of water management and lack of access to tractor services for land preparation at the appropriate timing for planting. However, there have been no field experiments to demonstrate the potential of rice cultivation in the floodplain ecosystems in West Africa. The objective of this study was to determine rice productivity and the responses to various fertilizer applications on different topographical positions within floodplain ecosystems. Three years of field experiments were conducted in no-till and no-bund conditions in various topographical positions including flood-prone areas with no farming history near back-swamps and conventional farmlands in the middle to upper slopes along a transect away from the White Volta River. The effects of different combinations of S, P and K fertilizer were evaluated with a constant rate of 60 kg N ha^{-1} applied as urea or ammonium sulfate. Rainfall varied widely, with heavy rainfall during the initial growth stage in 2012, a long dry spell during the middle stage in 2013, and consistent rainfall in 2014. Both grain yields and responses to N application tended to increase at lower elevations and near the river, benefiting from the carbon- and clay-rich soils and moisture availability, except when a submergence stress suppressed grain yield in the lowest field in 2012. The yield response was amplified with S application. On average, application of S resulted in an increase of agronomic N use efficiency from 13.4 to 22.8 kg grain per kg N applied. The effect of N and S applications were particularly large in the unutilized lowlands that produced the highest average yields ranging from 3.21 to 4.00 t ha^{-1}, compared to yields ranging between 0.38 and 1.40 t ha^{-1} achieved on conventional farmlands. Our results clearly showed empirical evidence of high productivity and high N use efficiency for rice particularly with S application in the currently unutilized floodplain areas under no-till and no-bund rainfed conditions. Although the risk of reduced yields due to complete submergence exists, cultivation of rice in productive floodplain areas offers good opportunities to increase rice production in West Africa.

1. Introduction

Faced with rapid population growth and increasing per capita rice consumption, increased production is required to meet the future demand for rice in West Africa. This increase can be achieved by a good balance between area expansion and production improvement per unit area. It is recognized that the gap between the potential and actual yields remains large in West Africa (e.g., Saito et al., 2013), and there are opportunities to increase total rice production by reducing this yield gap. However, van Oort et al. (2015) projected that even with high rates of yield increase in which the yield is increased up to 80% of the potential yield and rice cropping is doubled in all irrigated land by 2025, some area expansion would be still required to achieve rice self-sufficiency in many countries of West Africa. Therefore, as van Oort et al. (2015) noted, studies on the rice productivity in the currently unused land should be further promoted.

Abbreviations: ΔB_{60N}, the increase in the benefit to farmers relative to the control plots by applying 60 kg N ha^{-1}; AE_N, agronomic nitrogen use efficiency; AS, ammonium sulfate; CEC, cation exchange capacity; GHC, Ghana cedis (currency unit); HSD, Tukey's honestly significance test; TC, total carbon; TN, total nitrogen

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River floodplains, which are typically wide and flat alluvial plains, are a possible niche to expand the area under rice production in West Africa. This is both because most of this land is currently not utilized for agricultural production and because the land's characteristics are potentially suitable for rice production due to relatively abundant water supply and high soil fertility status. Andriesse and Fresco (1991) estimated the total area of river floodplains and lacustrine plains in West Africa at 21×10^6 ha, which is more than three times the size of the current area of rice cultivation in the region (FAOSTAT, 2012–2014). Among the major agro-ecological zones in West Africa, the river floodplain is mostly found in the Sudan and Guinea Savannas, which have vast areas of flat terrain along rivers such as the Niger, Benue, Chari, and Volta (WARDA, 2002).

The major constraints on the expansion of crop production into river floodplains include difficult water control, the risk of complete submergence of crops, and water-borne disease (Balasubramanian et al., 2007). The construction of an irrigation system or bunding would be ideal to more efficiently control flood water, but these infrastructural interventions are too costly for local farmers. A lack of access to roads also inhibits the operation of tractors for plowing during the appropriate planting periods. On the other hand, this ecosystem provides relatively rich alluvial soils and high moisture availability compared with upland areas (Andriesse, 1986; Buri et al., 1999). Moreover, the use of river floodplains for rice cultivation can reduce competition for land with other major crops (e.g., maize, yam, cassava), as these crops are less tolerant to submergence stress. Abe et al. (2010) performed an extensive soil survey in 13 countries of West Africa and demonstrated that floodplain soils are more fertile and possess higher clay contents and effective cation exchange capacities than soils in inland valleys, which currently represent one of the major rice-producing ecosystems in the region (Rodenburg, 2013). Various aspects of rice production in inland valleys have been studied, including the soil characteristics (Issaka et al., 1996), and rice production has been promoted through the development of appropriate cultivation management practices adapted to the hydrological and pedological variations within such valleys (Haefele and Wopereis, 2005; Touré et al., 2009). For instance, Touré et al. (2009) showed large variations in grain yield and in the effects of N fertilizer application and bund construction between different topographical locations within the inland valleys of West Africa.

However, few field experiments have been conducted to demonstrate the potential of rice cultivation and practical adaptation to the small-scale toposequence of the river floodplain of West Africa. Our previous surveys identified large variations in hydrological conditions and soil properties even within a relatively small area of the floodplain along a gentle slope away from the White Volta River (Tsujimoto et al., 2013; Yamamoto et al., 2012). For instance, the total carbon content of the soils increased exponentially (by more than 10 times) with increasing proximity to bodies of standing water (i.e., the main river and back-swamps). This suggests that different yield levels will be achieved and that site-specific management will be necessary to grow rice depending on the topographical location within the floodplain. In these previous studies, we also observed widespread soil sulfur deficiency, which could be another important factor that constrains the development of appropriate rice cultivation practices in the floodplain. Such S-deficient soils are reported to be widespread in West Africa (Acquaye and Beringer, 1989; Friesen, 1991; Yamaguchi, 1999; Buri et al., 2000). However, the response of rice grown in these soils to S application and the interaction with the toposequence gradient in the floodplain are poorly understood.

In the current study, we targeted a small-scale floodplain area along the White Volta River in northern Ghana as a test case for West Africa. The region belongs to Guinea savanna ecology and includes vast areas of flat land within the Volta basin. Analysis of satellite imagery showed that the region includes most of the seasonally flooded plains and swamps in Ghana (Kapetsky, 1991). Given the current constraints on using floodplain areas for farming, field experiments were conducted under no-till and no-bund rainfed conditions. Our objective was to determine the effects of topography and various N and S fertilizer combinations on rice productivity in river floodplain systems.

2. Materials and methods

2.1. Site description

Field experiments were conducted during the wet season (June to November) from 2012 to 2014 in a White Volta floodplain (9° 06'N, 1° 09' W) in northern Ghana. The major soils in the region are categorized as Lixisols and Plintosols (IUSS Working Group WRB, 2015). Katsura et al. (2016) described the meteorological data at the experimental site during the growing periods in each year. In summary, the average temperatures and the average solar radiation were 26.5–27.0 °C and 15.4–15.6 MJ m^{-2} day^{-1}, respectively. The rainfall pattern is described later in this paper. Tsujimoto et al. (2013) provides detailed geographical information and a map of the study site.

The farmers mainly grow upland crops such as maize, yam, cassava and groundnut, but also grow some rice at lower elevations under rainfed condition without bund construction. In contrast, the vast and flood-prone areas close to back-swamps or the river remain mostly unutilized for farming. Those flood-prone areas are covered by gramineous and cyperaceous weeds and are in most cases exposed to flooding during the rainy season and drying during the dry season (Supplementary Figure, S1). Prior to the start of the experiment in 2012, we established four small fields in the unutilized flood-prone areas that had no cropping history and selected two existing rice fields for the intermediate water condition and one existing drought-prone field at higher elevation; the sites extended along a transect away from the river. In total, we had seven experimental fields: L1 (a drought-prone field, located farthest from the river), L2 and L3 (intermediate rainfed fields with a history of lowland rice cultivation), and L4 to L7 (unutilized flood-prone fields with no cultivation history). These sites are ranked in order from the highest elevation and greatest distance from the river (117 m asl and 3498 m for L1) to the lowest elevation and shortest distance from the river (91 m asl and 2349 m for L7). The elevation was sequentially measured using a GPS device (VISTA eTrex, Garmin Ltd., Olathe, KS, USA). The distance from each site to the river was determined using a QuickBird image and the GIS functions of the ArcView software. The experimental fields were only a few hundred meters apart from one another, but were selected to cover a wide range of hydrological and pedological variations based on our previous surveys on topographical distribution of the waterlogging length during the rainy season in 2010 (Yamamoto et al., 2012) and of soil total carbon contents (Tsujimoto et al., 2013). The surface soils were taken from 0 to 15 cm as composites of 4 cores from each field prior to the start of each season. Table 1 summarizes the mean physical and chemical properties of the soils in each experimental field over three years. The total carbon (TC) and total nitrogen (TN) contents of the soils were determined by the dry combustion method using automatic highly sensitive NC analyzer, Sumigraph NC-220F (SCAS, Japan). Soil texture was determined by sieving and pipetting method. Mineralizable nitrogen was determined by a 4-week anaerobic incubation at 30 °C as the amount of NH_4^+-N extracted with 10% KCl solution. The available phosphorus content was measured by Bray No.2 method (Bray and Kurts, 1945). The extractable sulfate (S) was determined by extraction with a Ca $(H2PO4)_2$ solution containing 500 mg P l^{-1} (Fox et al., 1964). The cation exchange capacity (CEC) was measured using the ammonium acetate extraction method at pH 7.0. The TC of the soil was positively correlated with the TN content, clay content, amount of mineralizable N, and CEC. TC and the other variables generally increased moving from the highest elevation (L1) to the lowest (L7), with increasing proximity to the river. The main exception was site L3, which had a lower TC content and sandier soils than the adjacent sites. Based on these physical and chemical properties, soil fertility was determined