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Limited Si-nutrient status of rice plants in relation to plant-available Si of soils, nitrogen fertilizer application, and rice-growing environments across Sub-Saharan Africa

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ABSTRACT

Rice is a specific silica-accumulator among higher plants. The Si in rice enhances resistance to biotic and abiotic stresses. The booming demand for rice in Sub-Saharan Africa (SSA) requires rapid increases in rice production, and hence more Si supply will be needed from soils, irrigation water, and external inputs. However, the current Si-nutrient status of rice plants and relevant factors has been so far paid little attention in the region. Therefore, an extensive survey was conducted for evaluating variability of Si concentration in rice straw in relation to soil properties, fertilizer management practices, and rice-growing environments across a wide range of local farmers' fields in SSA. Plant and soil samples were collected at harvesting time from 99 fields in Benin, Ghana, Guinea, Kenya, Madagascar, Mozambique, and Nigeria, and then chemically analyzed. The Si concentration in straw ranged 1.7–8.4%, and the values in 68% of the fields were below the critical deficiency level of 5%. The Si concentration in straw was most significantly correlated with the amounts of water-soluble Si in soils after 1-week anaerobic incubation at 40 °C (hereafter, plant-available Si). The plant-available Si was particularly low in the acidic soils of Highland and Humid Agro-ecological zones, mainly consisting of weathered Oxisols and Ultisols. The mean Si values were greatest in the order of irrigated lowland (5.3%) > rainfed lowland (4.3%) > upland (3.4%) among different rice-growing environments. Multiple regression analysis revealed that 59% of the variation in Si concentration in straw was explained by the plant-available Si in soils, rice-growing environments, N application rates, and mineralizable N in soils. The regression model indicated that improvement of plant-available Si in soils could increase the Si concentration in straw at a rate of 0.043% per mg kg^{-1}, while external N application lowered the Si concentration in straw at a rate of 0.0068% per kg N ha^{-1} input. This extensive survey revealed that low Si nutrient status was widely observed for rice as associated with limited plant-available Si in the SSA soils. The probability of Si deficiency can be increased with abundant N application and non-submerged field conditions. By focusing on these Si-deficient field conditions, further studies should quantify the relationship between Si-nutrient status and occurrence of environmental stresses such as blast infection so as to develop appropriate Si-management practices for rice production in SSA.

1. Introduction

Rice plants take up Si from soils at levels several-fold greater than the essential macronutrients, such as N, P, and K. The critical deficiency level of Si in rice straw is indicated at 5%, while the typical observed ranges of N, P, and K in straw are 0.51–0.76%, 0.07–0.12%, and 1.17–1.68%, respectively (Dobermann and Fairhust, 2000). The ability of rice to absorb Si is prominent compared even to the other gramineous plants, such as wheat, triticale, sorghum, rye, maize, and barley, known as specific Si-accumulating species among the higher plants (Tamai and Ma, 2003). The role of Si includes increasing resistance to fungal diseases (e.g., rice blast, brown spot, sheath blight), to insect attacks, and to abiotic stresses including drought and lodging (Savant et al., 1997; Ma, 2004). The physiological mechanisms behind these beneficial phenomena are yet to be clarified but are partly attributed to the glass-like coating of polymerized SiO_2 on epidermal surfaces (Yoshida et al., 1962b). This hard coating hypothetically shapes robust rice plants and physically blocks fungal and insect attacks (Volk et al., 1958; Yoshida et al., 1962a,b). Rodrigues et al. (2004) recently demonstrated a biochemical role

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Abbreviations: AEZs, Agro-ecological zones; SSA, Sub-Sahara Africa; TC, total carbon; TN, total nitrogen.

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for Si in stimulating the terpenoid pathway and the synthesis of momilactone phytoalexins that contribute to the improvement of rice resistance to blast. Si also alleviates mineral stresses, such as P deficiency, Al toxicity, Mn toxicity, and Zn toxicity as associated with the detoxification of metal ions by increasing the pH and formation of metal silicate precipitates in the rhizosphere, increasing the oxidizing capacity of the root system, and co-localizing toxic elements into less-active tissues (Okuda and Takahashi, 1962; Ma and Takahashi, 1991a; Cocker et al., 1998; Gu et al., 2012; Li et al., 2012).

The booming demand of rice in Sub-Saharan Africa (SSA) requires rapid increases in rice production. Hence, a larger Si supply will be needed from soils, irrigation, and external inputs to guarantee the beneficial effects of Si for rice production as indicated above. In many parts of the SSA, soils are highly weathered, as represented by Oxisols, Ultisols, and Alfisols, and, to date, no specific Si management practices have been practiced. The weathered soils largely consist of 1:1 layered kaoline group minerals, quartz, and aluminum and iron oxides that have low Si solubility compared to 2:1 layered and amorphous minerals (Drees et al., 1989). Given the nature of weathered soils, there is an expected risk of Si deficiency while increasing rice production in SSA. We previously reported by using lowland soils in eastern Madagascar that excessive increases in N uptake and biomass production resulted in significant dilution of Si in plant tissues, which consequently caused severe damage to grains from blast disease (Tsujimoto et al., 2010). The blast disease, as one of the major constraints to rice production in SSA, has been increasingly reported where farming practices are intensified by using high-yielding varieties with abundant mineral fertilizer inputs and in upland field condition in West Africa and in the highland of Madagascar (Fomba and Taylor, 1994; Raboin et al., 2012; Kihoro et al., 2013). Winslow (1992) demonstrated a beneficial effect of Si fertilization on controlling the occurrence of blast disease by using the upland Oxisols in Nigeria, and noted the possibility of widespread Si deficiency to satisfy the requirements of rice plants. These findings imply that improvement of Si nutrient status may become a key agronomic component for increasing the resistance of rice plants to environmental stresses such as blast disease while intensifying rice production in SSA.

However, until now, there have been no extensive surveys conducted to identify the nature and magnitude of the problems with plant Si nutrition and Si availability in the soils for rice production in SSA. The available Si in soils was conventionally assessed by using acid reagents such as acetate buffer method (Imaizumi and Yoshida, 1958), whereas water-soluble Si has been recognized as a measure at near equilibrium with the soil system and to avoid over-extraction of Al-bound Si by acid reagents that are not easily available for plant uptakes (Ma and Takahashi, 2002). The kinetics of Si solubility is also affected by the other soil factors such as organic matter and particle sizes, and pH, temperature, degree of reduction and water content that can differ among rice-growing environments (Savant et al., 1997). In this study, we first collected plant and soil samples from wide-range of local farmers' fields for evaluating the nutrient status of rice plants in terms of Si concentration in straw across SSA. Then we analyzed the variability of Si concentration in straw in relation to the rice-growing environments, soil properties, and fertilizer management practices so as to specify the target factors causing Si deficiency for rice production.

2. Materials and methods

2.1. Site description and sample collection

Rice plants and soil samples were collected at maturity from a total of 99 local farmers' fields in Benin ($n = 21$), Ghana ($n = 34$), Guinea ($n = 4$), Kenya ($n = 2$), Madagascar ($n = 17$), Mozambique ($n = 5$), and Nigeria ($n = 16$) during the main rice-growing periods (rainy season) at each location in 2006–2011. These seven countries accounted for 55.8% of the total rice production in SSA (FAOS database, 2012). The sample fields were located with GPS devices or with Google Earth using the village names and dotted onto an agro-ecological zoning map in Fig. 1 (http://harvestchoice.org/about/harvestchoice/intellect.html). The sampling points were classified into Semi-arid ($n = 8$), Sub-humid ($n = 68$), Humid ($n = 11$), and Highland ($n = 12$) agro-ecological zones (AEZs) in the tropics. The sample fields were managed by local farmers including 19 on-farm trials and consist of 20 irrigated lowlands, 68 rainfed lowlands, and 11 rainfed uplands. The rainfed lowland environment included two submergence-prone floodplain fields along the White Volta River in the northern region of Ghana, while the others were located within the flat and gently-sloping lowland areas having intermittent to continuous water standing during the rice-growing periods. Amounts of external N input were calculated from the experimental design for the 19 on-farm experiments and estimated for the others by interviewing to identify types and amounts of fertilizer the local farmers used. At harvest, a number of average-sized hills were selected at each field. Then, the aboveground plant parts were collected and separately composited into grain and straw samples. The soil samples were taken from 0 to 15 cm depth as composites of two to three cores.

2.2. Plant and soil analysis

The straw samples were oven-dried at 80 °C to a constant weight and ground into fine powders using a high-speed vibrating sample mill (Model T1-100, Heiko Co Ltd., Fukushima, Japan). The plant tissues were then analyzed for Si concentration by the dilute hydrofluoric acid extraction and spectrometric molybdenum method (Saito et al., 2005). The soil samples were air-dried at room temperature and sieved through a 2-mm mesh prior to chemical analysis. The amounts of soluble silica were determined by two methodologies as candidate indices to assess plant-available Si in soils: (1) water-soluble Si after a 1-week anaerobic incubation at 40 °C (Takahashi and Nonaka, 1986a) and (2) acetate buffer-soluble Si at pH 4 (Imaizumi and Yoshida, 1958). The pH was measured in a 2.5:1 distilled water–soil solution. Clay content was determined by the sieving and pipette method (Gee and Bauder, 1986). Analysis of total carbon (TC) and nitrogen (TN) contents and mineralizable nitrogen were added as indices of organic matter contents and general fertility of the soils. The total carbon (TC) contents and total nitrogen (TN) contents of soils were determined using an automatic highly sensitive NC analyzer, Sumigraph NC-220F (SCAS, Japan). The mineralizable nitrogen was determined by a 4-week anaerobic incubation at 30 °C as the amounts of NH_4^+-N extracted with a 10% KCl solution (Japanese Society of Soil Science and Plant Nutrition, 1996).

2.3. Statistical analysis

A statistical analysis was performed using JMP 8 software (SAS Institute Inc.). Tukey's HSD test was conducted to compare the means of measured variables among different AEZs, and means of Si concentration in straw among different rice-growing environments, i.e., irrigated lowland, rainfed lowland, and upland. A *t*-test for the simple regression coefficient was conducted to identify the interrelationship of the soil properties, i.e., the water-soluble Si, acetate-soluble Si, pH, TC contents, TN contents, mineralizable N, and clay contents. A stepwise regression analysis was repeated to identify factors that explained variation in Si concentration in straw at maturity. The candidate factors included the rice-growing environments, N application rates, and all the soil properties.