Assessing Silicon Availability in Soils of Rice-Growing Lowlands and Neighboring Uplands in Benin and Nigeria

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Abstract: Silicon (Si) is known as a beneficial nutrient in the cultivation of rice, playing a key role in photosynthesis enhancement, lodging resistance and tolerance to various environmental stress. The present study aimed to examine available Si content in both lowland soils (n = 29) and neighboring upland soils (n = 21) collected from Benin and Nigeria and to evaluate the validity of the assessment results through a pot experiment. Our results revealed that the acetate-buffer method predicted Si concentration in rice straw at the harvest stage (R² = 0.68, P < 0.01) better than the anaerobic-incubation method (R² = 0.31, P > 0.05), and 76% of the uplands and 38% of the lowlands were deficient (< 50 mg/kg) in acetate-buffer soluble Si. These findings suggest that the Si-deficiency soils prevail across the study area, making rice plants starved for Si and prone to environmental stress.

Key words: Oryza sativa L.; silicon; upland field; lowland field

Rice is known as a silicon (Si)-accumulating plant which contains Si at levels up to 10% in dry matter weight (Ma and Yamaji, 2006). Silicon plays beneficial roles in rice plants such as photosynthesis enhancement and lodging resistance (Matoh et al., 1991; Agarie et al., 1992) and helps improve tolerance to biotic and abiotic stress (Savant et al., 1997a; Ma, 2004). Therefore, Si has been long recognized as a key nutrient to improve and stabilize rice yields in Japan (Savant et al., 1997b; Ma and Takahashi, 2002) and has recently been attracting increasing attention in many other Asian countries. Moreover, the plant-available Si in the form of soluble silicate is seriously limited by its low solubility (Sommer et al., 2006). There has been an ongoing need for methods to assess the amount of plant-available Si in the soils of rice-growing regions, and such methods will provide useful information for developing countermeasures for rice Si deficiency and estimating the proper application rate of Si-containing material for soil Si replenishment (Ma and Takahashi, 2002).

Several methods for the assessment of soil-available Si have been developed in Japan to predict the silicon concentration in rice straw, in particular the flag leaf at the harvest stage (Ma and Takahashi, 2002). Of these methods, the acetate-buffer method (Imaizumi and Yoshida, 1958) and the anaerobic-incubation method (Takahashi and Nonaka, 1986) have been widely adopted to lowland paddy soils in Japan and some part of temperate Asia (Ma and Takahashi, 2002). However, much less effort has been devoted to estimating Si availability in tropical paddy soils. Further, very little attention has been paid to measuring Si in upland rice soils (Juo and Sanchez, 1986) despite upland rice ecology being widespread in the tropics such as Latin America and West Africa (Winslow, 1992; Winslow et al., 1997). It is consequently said that no reliable method has been developed so far to predict the need for Si application in tropical soils (Savant et al., 1997a).
In West Africa, the widespread distribution of highly weathered soils, such as Ultisols, Oxisols and Alfisols (Eswaran et al., 1997; Hirose and Wakatsuki, 2002), represents a potential risk of Si deficiency (Juo and Sanchez, 1986). Si deficiency problems may occur more frequently where rice production is being expanded, as it is in West Africa (Abe and Wakatsuki, 2011). Si deficiency can make rice plants more susceptible to environmental stress (Savant et al., 1997a) and may hamper sustainable rice productivity improvement.

Tsujimoto et al. (2014) demonstrated that rice straw having Si concentration below a critical level (5% in dry matter) can be found in 68% of rice fields across west African regions, and that the anaerobic-incubation method has better capacity to assess soil-available Si than the acetate-buffer method. However, they examined much fewer upland rice soils (n = 11) than lowland soils (n = 88) despite the former occupying about one half of rice-cultivated area in the region (Abe and Wakatsuki, 2011). In general, upland rice contains a smaller amount of Si in its body than lowland rice (Winslow, 1992; Winslow et al., 1997) as soil Si availability is affected substantially by the degree of submergence (Takahashi, 1974). Also, it is generally said that about 50% of Si taken up by lowland rice originates from the soil in Japan (Japan Soil Association, 2014). These findings suggest that there are different mechanisms of Si supply between lowland and upland soils.

This background highlights the need for the assessment of Si availability in rice-growing soils of West Africa, as well as the need to develop an appropriate assessment method for soil Si availability which is applicable for both upland and lowland soils.

The present study therefore aimed to assess available Si content in lowland soils and neighboring upland soils in Benin and Nigeria and to examine the validity of the assessment methods through a pot experiment.

**MATERIALS AND METHODS**

### Field sampling and soil analysis

Soil samples were collected from the topsoil (0–15 cm)
of 29 lowland and 21 neighboring upland sites in Benin and Nigeria (Table 1). The lowland sites are mostly located in inland valley swamps, which were largely planted with rice at the time of soil sampling. The neighboring upland sites are situated on hills, plateaus or natural levees with good drainage. These upland sites nearby the lowland sites were widely cultivated with maize at the survey period, but all of them had the potential for rice cultivation.

Soil analysis was made for fine earth samples which were prepared through air drying and sieving (ϕ = 2 mm). Available Si was extracted by the acetate-buffer method (Imaizumi and Yoshida, 1958) as well as by the anaerobic-incubation method (Takahashi and Nonaka, 1986). In detail, 5 g soil sample was extracted with 50 mL of 1 mol/L sodium acetate (pH = 4) at 40 °C for 5 h for the acetate-buffer method, whereas 10 g soil sample was incubated with 60 mL water at 40 °C for one week in the anaerobic-incubation method. Concentrations of phosphorus (P) and Si in the extracts were determined separately by the molybdenum-blue method according to Japan Soil Association (2001).

Soil pH was measured in water (soil:liquid = 1:1) using the glass-electrode method (9625-10D connected to D-55, HORIBA, Tokyo, Japan). The contents of organic carbon (C) and total nitrogen (N) were simultaneously determined by the dry combustion method using NC-22A (Sumika Chemistry, Tokyo, Japan). Here, the total amount of C in the samples was considered to be in an organic form because no effervescence was observed after the addition of 0.5 mol/L hydrochloric acid. Available P was extracted by the Bray No. 2 method (Bray, 1945). Exchangeable calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) were extracted with 1 mol/L neutral sodium acetate, and their concentrations were determined by an atomic adsorption spectrometer (Z-2300, Hitachi, Tokyo, Japan). Exchangeable acidity was measured by the alkaline-titration method after the extraction with 1 mol/L potassium chloride. Effective cation exchange capacity (ECEC) was calculated by the summation of exchangeable bases and acidity.

**Pot experiment and plant analysis**

A pot experiment was carried out at the International Institute of Tropical Agriculture Benin Station, Abomey-Calavi (06°25’ N, 02°19’ E) during the period of December 2011 to April 2012. This station is situated under the coastal savanna agro-climatic zone (mean annual daily air temperature is 27 °C and mean annual rainfall is 1 200 mm). A total of 16 soil samples (32% of the sample set; 9 from the lowlands and 7 from the uplands) were selected and used for the pot experiment.

A total of 7 kg soil sample (oven-dry weight basis) was placed in a 7 L plastic pot. Six seeds of *Oryza sativa* L. cv. SIIPl92033 designated as FARO44 in Nigeria, a widely adopted variety for both upland and rainfed lowland environments in Nigeria, were sown in each pot and then thinned to two seedlings per pot at 14 d after seeding (DAS). The lowland soil pots were kept submerged by water after 14 DAS, while the upland soil pots were considered to be well-drained throughout the experimental period due to the presence of perforated holes in the pot bottoms. One gram of multi-element fertilizer (26 g m⁻²) (Super Master, AGRI-MAT Ltd., Accra, Ghana: N, 20%; P₂O₅, 20%; K₂O, 20%; B₂O₃, 0.02%; CuO, 0.005%; Fe₂O₃, 0.07%; MnO, 0.03%; ZnO, 0.01%) was basally applied to the pot, and 1 g of urea (5.2 g/m²) was given at the panicle formation period. A randomized complete block design was adopted with triplicates, and means of these triplicates were used for the correlation analysis.

Rice panicle and straw were sampled separately at the harvest stage. The number of panicles per pot was counted manually and then all grains were removed from the panicle by threshing. Filled grains were separated from unfilled ones by water. Hundreds of filled grains selected at random were weighed to calculate the 1000-grain weight. Grain yield was expressed on a paddy basis at 14% moisture content.

Straw samples were finely ground by a ball mill after drying at 80 °C for 48 h. The powder samples obtained thereby were used for the measurement of organic C and total N and were digested with a mixture of nitric acid, hydrogen peroxide and hydrofluoric acid in a microwave system (MWS-2, Berghof Co, Eningen, Germany) for the analysis of Si by the atomic adsorption spectrometer (Z-2300, Hitachi, Tokyo, Japan).

**RESULTS**

**Soil-available Si content and general fertility characteristics**

Out of 21 pairs of soil samples collected from
lowlands and their neighboring uplands, 70%–80% of the pairs showed a lower pH value but higher contents of organic C and total N in the lowland than in the upland (Fig. 1). The majority of the pairs had similar values in available P between the lowland and the upland, although some pairs gave much higher values in the upland than in the lowland. Regarding available Si, both the anaerobic-incubation soluble Si and the acetate-buffer soluble Si had a higher value in the lowland than in the upland in about half of the pairs (Fig. 2).

There was little correlation \((n = 50, R^2 = 0.23, P > 0.05)\) between the anaerobic-incubation and the acetate-buffer soluble Si. The correlation analysis for the upland soils revealed an extremely significant positive correlation of the acetate-buffer soluble Si with organic C, total N and ECEC, respectively (Table 2). In contrast, there was insignificant correlation between these parameters with respect to the lowland soils, except for ECEC, which showed a significantly positive correlation with the acetate-buffer soluble Si.

**Rice nutrient concentrations and agronomic traits**

Si concentration in rice straw at the harvest stage varied from 18.4 to 30.5 mg/kg for the lowland rice and from 11.3 to 30.0 mg/kg for the upland rice (Fig. 3). The rice straw Si concentration significantly correlated with the available Si content obtained by the acetate-buffer method \((R^2 = 0.68, P < 0.01)\), but was not correlated with that by the anaerobic-incubation method \((R^2 = 0.31, P > 0.05)\).

As expected, the Si concentration in rice straw had significant positive correlations with grain yield and number of panicles per pot, respectively (Table 3). Also, Si concentration in rice straw grown in lowland

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**Fig. 1.** Soil pH and contents of organic C, total N and available P in soil samples.

**Fig. 2.** Contents of acetate-buffer soluble Si and anaerobic-incubation soluble Si in soil samples.

**Table 2.** Correlation analysis of acetate-buffer soluble Si content with selected properties of soil samples.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Acetate-buffer soluble Si</th>
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<tbody>
<tr>
<td></td>
<td>Lowland ((n = 29))</td>
</tr>
<tr>
<td>pH</td>
<td>0.74***</td>
</tr>
<tr>
<td>Available P</td>
<td>0.22</td>
</tr>
<tr>
<td>Total N</td>
<td>0.18</td>
</tr>
<tr>
<td>Organic C</td>
<td>0.20</td>
</tr>
<tr>
<td>Exchangeable K</td>
<td>0.51**</td>
</tr>
<tr>
<td>Exchangeable Ca</td>
<td>0.77***</td>
</tr>
<tr>
<td>Exchangeable Mg</td>
<td>0.42*</td>
</tr>
<tr>
<td>Exchangeable Na</td>
<td>0.23</td>
</tr>
<tr>
<td>Exchange acidity</td>
<td>-0.19</td>
</tr>
<tr>
<td>ECEC</td>
<td>0.64***</td>
</tr>
</tbody>
</table>

*ECEC, Effective cation exchange capacity.
***, ** and *** indicate significant correlations at the probability of 0.05, 0.01 and 0.001 levels, respectively.
soils was positively correlated with its C, N, K, Ca and Mg concentrations to a significant degree. These nutrients also showed significant positive correlation with the Si concentration in rice straw grown in upland soils, except for Ca, which had a significant negative correlation with Si content.

**DISCUSSION**

The better correlation of Si concentration in rice straw with the acetate-buffer soluble Si content than with the anaerobic-incubation soluble Si content indicates that the acetate-buffer method has a superior capacity of assessing Si availability in the studied soils. However, our result conflicts with that of Tsujimoto et al (2014) who reported a higher correlation of Si concentration in rice straw with the anaerobic-incubation method than with the acetate-buffer method. The difference is that our sample set includes certain number of soils (42% of the data set), while that used by Tsujimoto et al (2014) focuses predominantly on lowland soils (89% of the data set). The anaerobic-incubation method seems not to reflect the actual situation seen in upland environments, and it may dissolve that Si is insoluble under aerobic soils, where anaerobic conditions are the rare situation. In contrast, the anaerobic-incubation method reflects the lowland (anaerobic) condition well. This may be the reason why Tsujimoto et al (2014) found a better result with the anaerobic-incubation method than with the acetate-buffer method. Moreover, Nonaka and Takahashi (1988) warned that the acetate-buffer method may over-estimate the available Si content in soils which are subjected to application of Si-containing materials. However, for now, rice farmers in West Africa have not applied such materials to their soils, except for rice straw as a harvest residue. Also, Nonaka and Takahashi (1988) pointed out the risk of over-estimation of available Si due to dissolution of Fe- and/or Al-bound Si, which is not easily available for rice plants. This would be especially a matter of concern in the upland soils, which generally have higher contents of Fe/Al oxyhydroxides than the lowland soils (Juo and Sanchez, 1986; Abe and Wakatsuki, 2010). However, this seems not to be the case in our study since the acetate-buffer method yielded a better result than the aerobic-incubation method. As a consequence, we recommend the use of the acetate-buffer method for the assessment of soil Si availability, especially in upland rice fields in West Africa.

Table 3. Correlation matrix of Si concentration with concentrations of other nutrients in rice straw and with grain yield and yield components of rice (n = 16).

<table>
<thead>
<tr>
<th>Elementalal composition and agronomic trait</th>
<th>Lowland</th>
<th>Upland</th>
</tr>
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<tbody>
<tr>
<td>C</td>
<td>0.96***</td>
<td>0.90***</td>
</tr>
<tr>
<td>N</td>
<td>0.89***</td>
<td>0.86***</td>
</tr>
<tr>
<td>P</td>
<td>0.65**</td>
<td>0.68**</td>
</tr>
<tr>
<td>K</td>
<td>0.71**</td>
<td>0.90***</td>
</tr>
<tr>
<td>Ca</td>
<td>0.74**</td>
<td>-0.77**</td>
</tr>
<tr>
<td>Mg</td>
<td>0.91***</td>
<td>0.58*</td>
</tr>
<tr>
<td>No. of panicles per pot</td>
<td>0.90***</td>
<td>0.76**</td>
</tr>
<tr>
<td>No. of spikelets per panicle</td>
<td>0.30</td>
<td>0.24</td>
</tr>
<tr>
<td>Seed-setting rate</td>
<td>-0.02</td>
<td>-0.13</td>
</tr>
<tr>
<td>1000-grain weight</td>
<td>-0.26</td>
<td>-0.44</td>
</tr>
<tr>
<td>Grain yield</td>
<td>0.97***</td>
<td>0.74**</td>
</tr>
</tbody>
</table>

*, ** and *** indicate significant correlation at the probability of 0.05, 0.01 and 0.001 levels, respectively.
The acetate-buffer extractable Si content in the studied soils was generally low, showing a deficiency of available Si, i.e., less than 50 mg/kg (Ma and Takahashi, 2002), in 76% of the upland soils and 38% of the lowland soils. The widespread Si deficiency may be related to the widespread distribution of highly weathered soils with sandy and/or siliceous nature and/or with low-activity clays in West Africa (Kang and Spain, 1986; Hirose and Wakatsuki, 2002; Abe et al, 2010). The Si deficiency in the study region would make rice plants susceptible to environmental stress (Ma, 2004) and result in unstable and decreased rice yields (Savant et al, 1997b).

The correlation analysis suggests different sources of soil-available Si between the lowland and upland environments. Very high correlations of acetate-buffer soluble Si with organic C and total N suggest that soil organic matter is a source of available Si in the upland soils, whereas their low correlations in the lowland soils (the exception being ECEC) imply that weatherable silicate clay minerals such as smectite and illite that occur preferentially in prolonged wet conditions can provide plant-available Si in the lowlands. Previous studies (Nakada, 1980; Ma and Takahashi, 1989; Sumida and Ohyama, 1991; Sistani et al, 1997) have revealed that the application of rice straw and organic amendments can improve rice Si status, suggesting the role of soil organic matter as an important source of Si for rice. Moreover, soil pH is likely to affect soil-available Si, namely, Si availability is low in acidic soils, as reported by Tsujimoto et al (2014). The higher Si availability but the lower pH value found in the lowland soils than the upland soils support that the degree of submergence also affects soil-available Si (Takahashi, 1974).

The significant positive correlations between rice straw Si concentration, grain yield and number of panicles per pot suggest that in the study region at least, Si is important for improving rice tillering capacity that eventually leads to increased rice production. Our results did not support Tsujimoto et al (2014), who suggested that application of N fertilizer results in reduction of Si concentration in rice straw in the Africa continent-wide assessment because of the significant positive correlation that we found between Si and N in rice straw. Moreover, the cause of the significant negative correlation found between Si and Ca in rice straw in the upland soils remains unclear. Probably, this conflicting result may come from the contrasting degrees of submergence between the lowland and the upland which affects Si availability and Ca supply in the soil.

**CONCLUSIONS**

The acetate-buffer method resulted in better prediction of the Si concentration in rice straw at the harvest stage than the anaerobic-incubation method. The acetate-buffer method can be applied for the assessment of soil-available Si in both lowland and upland soils, and 76% of the uplands and 38% of the lowlands investigated in this study had a deficient level of acetate-buffer extractable Si content (< 50 mg/kg). Soil-available Si may be associated with soil organic matter in the upland, but with weatherable silicate clay minerals in the lowland.

The low Si availability in the soils of the study region reflects the widespread distribution of highly weathered soils. Si deficiency will make rice susceptible to various environmental stress and can be a major factor that impedes rice production increase. To tackle this constraint, we recommend the supplemental use of locally available, farmer-affordable Si-containing materials such as rice straw, husk ash and livestock manure (Nakada, 1980; Ma and Takahashi, 1989; Sumida and Ohyama, 1991; Sistani et al, 1997). Such practices are also helpful for the prevention of further mining of soil-available Si and for the next step towards soil Si replenishment. Artificial fertilizers such as calcium silicate and silicate slags are often expensive or not available locally, and their use may not be economically efficient in West Africa (Alvarez et al, 1988; Alvarez and Datnoff, 2001), even though they are agronomically effective for rice farming in the region (Yamauchi and Winslow, 1989).

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