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ORIGINAL ARTICLE

Silica availability in soils and river water in two watersheds on Java Island, Indonesia

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Abstract

Silicon is a beneficial element for rice plants and is one of the major factors affecting the sustainability of rice production. We investigated silica (Si) availability and dynamics in soils of sawah, other land uses, and also in river and canal water in two watersheds in Citarum and Kaligarang, Java Island, Indonesia. The term sawah refers to a leveled and bounded rice field with an inlet and an outlet for irrigation and drainage, respectively. In the present study, we examined Si content in soils, plants and river water in relation to factors influencing the Si content, such as parent material and land use. The available Si content in sawah was found to be deficient at two sites and low at 10 sites out of 16 sites investigated in the Citarum watershed. In the Kaligarang watershed, no sawah site was classified as deficient and nine out of the 15 sawah sites were determined to be low for rice plant growth. A survey of Si content in rice flag leaves in some selected rice fields showed that seven out of 12 samples had contents less than 125 g SiO_2 kg^{-1}; these rice samples with low Si contents were those in sawah classified as low in Si contents. In the Citarum watershed, sawah soils developed from the accumulation of lake and clay sediment contained relatively little available Si, while sawah soils in the Kaligarang watershed that were mainly developed from tuff and volcanic ash contained relatively more available Si. In the Citarum watershed, the type of land use influenced Si availability in the soils via a large amount of litter accumulation of pine trees in the case of pine plantations, and acidification in the soils in the case of tea plantations and maize fields. In general, the Si content in river and canal water was higher in the Kaligarang watershed than in the Citarum watershed, and this appears to be affected by the type of parent material. In addition to the type of parent material, Si depletion occurring in dams might also influence Si content in the lower stream of river or canal water in the Citarum watershed.

Key words: available silica, parent material, rice, sawah, silica deficiency.

INTRODUCTION

Silicon is the second most abundant element on earth, accounting for 26.8% by weight (Faure 1991), and is present in all mineral soils (Klein and Hurlbut 1985). However, very few studies have examined silicon and its role in agriculture. Silicon is known to be a beneficial element for rice and sugarcane (Epstein 1999; Imaizumi and Yoshida 1958; Matichenkov and Calvert 2002), although it does not meet the criteria of an essential element. Many studies have examined the effect of silicon against plant diseases. Silicon can control plant diseases such as blast disease and sheath blight in rice and powdery mildew in cucumber (Ishizuka and Hayakawa 1951; Kawashima 1927; Miyake and Takahashi 1983). Silicon is also able to improve the drought tolerance of sorghum (Hattori *et al.* 2005). An important function of silicon has also been reported with respect to soil fertility, and Iler (1979) observed that silica (Si) is able to displace phosphate ions from the soil surface. However, studies examining the effects of silicon on soil fertility are still limited. Silica is defined as the silicon content in the weight of SiO_2 in soil and water.

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The distribution of Si in soils is influenced by the parent material, climate, vegetation, texture, pedogenesis and intensity of weathering (Hallmark *et al.* 1982). The total amount in soil is approximately 330,000 mg SiO_2 kg^{-1} (Bowen 1966); Kawaguchi and Kyuma (1977) reported that the soil-available Si content in tropical Asia ranged from 104 to 629 mg SiO_2 kg^{-1}. The available Si level in soil ranged from 50 to 250 mg SiO_2 kg^{-1} depending on the different extraction method used (Sumida 2002), which was governed by soil temperature, redox potential (Eh), soil pH and Si concentration in the soil solution in the fields (Sumida 1992). Soil in Indonesia has the highest available Si content among Asian countries (Kawaguchi and Kyuma 1977). However, studies have shown that the available Si in sawah soils in Java over the past three decades has decreased by approximately 11–20% (Darmawan *et al.* 2006). The term sawah in the present study refers to a leveled and bounded rice field with an inlet and an outlet for irrigation and drainage, respectively (Wakatsuki *et al.* 1998).

The source of Si for rice plants is derived from soil, irrigation water and plant residues, such as straw and rice husks if they were incorporated into the soil after harvest. Soils derived from the parent material of volcanic ash contain higher Si (Imaizumi and Yoshida 1958) than soils derived from alluvium material, particularly soil found in lowlands. As many rice fields and sawah are located in lowlands with the parent material mostly consisting of river sediment or alluvium, the original Si availability is generally low (Holmes 1939; Huang *et al.* 2006). Rice is a typical Si accumulator plant (Takahashi *et al.* 1981) that takes up Si from soil solution via an active mechanism (Ma *et al.* 2001, 2007). An intensive rice farming system requires an enormous amount of Si for rice production. A national survey of the Si contents of rice flag leaves in Japan conducted by the Ministry of Agriculture, Forestry and Fisheries in 1955 found that the contents ranged from 95 to 208 g SiO_2 kg^{-1} (Ma and Takahashi 2002). The critical value of Si content in rice flag leaves is defined as 75 g SiO_2 kg^{-1}, and levels less than 125 g SiO_2 kg^{-1} are considered to be deficient (Ma and Takahashi 2002). Rice plants absorb Si in the form of silicic acid ($SiOH_4$) from the soil solution. Once Si is adsorbed by the plant roots, it precipitates in the plant tissue as phytolith, also called opal, silicic gel or biogenic silica (SiO_2–nH_2O) along the cell walls or fills the cell lumen and the intercellular spaces (Alexander *et al.* 1997; Iler 1979; Saccone *et al.* 2006). However, the content of silicic acid in a plant ranges from only 0.5 to 8% of the total silicon in the plant (Yoshida *et al.* 1962). Therefore, Si in plant residues, including rice straw, is mostly found in the form of biogenic Si, which is unavailable to plants. Irrigation water is an important Si source in rice fields and accounts for approximately 30% of the Si uptake by rice plants (Imaizumi and Yoshida 1958). Recently, researchers found that Si is trapped in reservoirs or dams, resulting in a decrease in Si in outflow water (Ahearn *et al.* 2005; Harashima 2003). As there are three dams that operate in the Citarum watersheds, we are concerned about the Si retention in the dams.

As rice is the main staple food in Indonesia, the Indonesian government has encouraged improvements to the rice farming system through the extension of fertilizer and water management systems and new rice varieties. With these efforts, rice production in Indonesia has more than doubled in the past three decades (Food and Agricultural Organization of the United Nations Statistical Databases 2005). However, rice production has fluctuated and stagnated over the past decade (Food and Agricultural Organization of the United Nations Statistical Databases 2005). Aside from climatic factors, changes to soil fertility might have influenced recent stagnancy and fluctuations in rice production in Indonesia. In terms of soil fertility, researchers have examined nitrogen and phosphorus and continuously supplied fertilizers to sawah. However, other elements must also have been consumed more rapidly as rice production has increased. Soil-available Si is an important element for rice plants and should be examined and blast disease has threatened rice production from time to time and rice productivity has stagnated (Indonesian Ministry of Agriculture 2005). This might be an indication of an imbalance of nutrients, particularly Si, in sawah soils in Indonesia. Savant *et al.* (1997a,b) suggested that the stagnancy in rice productivity in the highly weathered soils of Africa, Asia and Latin America resulted from depletion of soil-available Si where dessilication occurred and farmers have not replaced the Si removed by the rice. However, there has been no research on Si availability in sawah soils in Indonesia. Therefore, a study on the current Si availability in soils is urgently required to examine rice production sustainability in Indonesia.

In the present study, we investigated Si availability in two watersheds in Java, which are the main rice production regions in Indonesia, and we discuss the Si availability in the sawah soils in relation to the parent material, land use, farming system and irrigation water.

MATERIALS AND METHODS

Study area

The present study was conducted in the Citarum and Kaligarang watersheds in the West and Central Java provinces. The study areas are located between latitudes 6°00′00″S and 7°00′00″S and longitudes 107°00′00″E

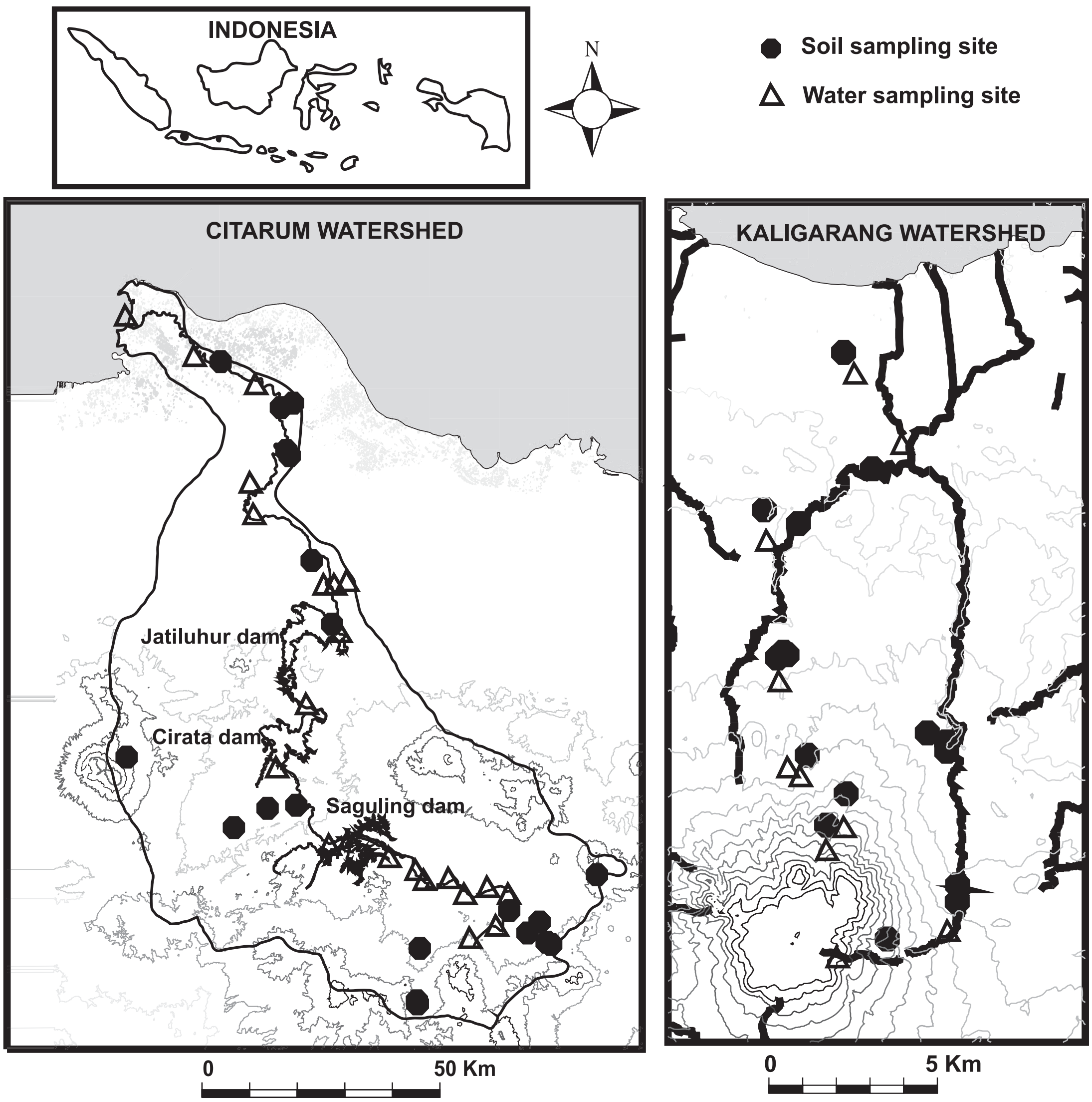

Figure 1 Map of the study area showing the soil and water sampling sites in the Citarum and Kaligarang watersheds.

and 108°00′00″E for the Citarum watershed and between latitudes 7°00′00″S and 7°15′00″S and longitudes 109°20′00″E and 109°30′00″E for the Kaligarang watershed. Details of the study areas and sampling sites are shown in Fig. 1. The study areas covered approximately 694,900 ha in Citarum and 21,000 ha in Kaligarang (Agus *et al*. 2004). There are three big dams in Citarum, namely Saguling, Cirata and Jatiluhur, located from upper to lower positions in that order. The mean annual rainfall and mean annual temperature in the study areas are 2,230 mm and 23.7°C for the Citarum watershed (1970–2000) and 1,856 mm and 25.8°C for the Kaligarang watershed (1990–2000). These data were collected from the Indonesian Agroclimate and Hydrology Research Institute.

Rice farming systems

In Citarum, rice is generally cultivated three times per year as long as irrigation water is available. Irrigation water is usually supplied through irrigation canals from the Jatiluhur dam throughout the year. Nitrogen, P and K are supplied at rates ranging from 46 to 184 kg N ha^{-1}, 36 to 72 kg P_2O_5 ha^{-1} and 6.3 to 63 kg K_2O ha^{-1}, respectively (information provided by surveyed farmers). However, KCl is rarely supplied, if at all, in most sawah in the watersheds. Chemical silicate fertilizer has never been supplied to the soil and Si has only been supplied from returning straw after harvesting and from irrigation water. In terms of straw management in Java, farmers prefer to burn it to shorten the time period before the next planting season and to avoid the spread of disease at some sites (Husnain, pers. comm., 2007).

Soil, plant and water sampling

Soil samples were collected at depths of 0–15 and 15–30 cm from 30 and 19 sites (Fig. 1) that were distributed from upper to lower topographical positions in different land-use areas in the Citarum and Kaligarang watersheds, respectively. Plant samples (rice flag leaves) were collected from several sites where the soils were sampled. Water samples were collected monthly from September 2006 until November 2007 along the Citarum and Kaligarang watersheds (Fig. 1) in collaboration with Jasa Tirta II Public Corporation and the Indonesian Soil Research Institute. There were 21 water-sampling points in the Citarum watershed and 10 in the Kaligarang watershed from the upper to lower stream of the rivers.

Laboratory analyses

The soil samples were air-dried and crushed to pass through a 2 mm sieve. The available Si in the soils was determined using the acetate buffer method (Imaizumi and Yoshida 1958). Soil samples were extracted in 1 mol L^{-1} acetate buffer (pH 4.0) at a ratio of 1:10 for 5 h at 40°C with occasional shaking. Although Sumida (1991) reported that the acetate buffer method was not suitable for soils previously amended with silicate fertilizer, this was not a problem in Indonesia because no silicate fertilizer had been applied. Rice plants were ground into powder using a tungsten carbide vibrating mixer mill and digested with HNO_3 in a high pressure Teflon Vessel (Koyama and Sutoh 1987; Quaker *et al.* 1970). The Si content in the soil and plant samples was determined using inductively coupled plasma-atomic emission spectroscopy (ICPS-2000; Shimadzu, Kyoto, Japan). The Si concentration in the water samples was determined using an atomic absorption spectrophotometer (Z-5000; Hitachi, Tokyo, Japan). The soil pH was measured using the glass electrode method with a soil : water ratio of 1:2.5 (International Institute of Tropical Agriculture 1979; McLean 1982). Total carbon (TC) of the soil samples was determined by the dry combustion method (Nelson and Sommers 1982) using an NC analyzer (MT-700; J-Science, Kyoto, Japan).

RESULTS AND DISCUSSION

Available-soil Si status

As there have been no studies examining the Si status of rice in Indonesian soils, we consulted reports from Japan and Russia where silicon research has been conducted. According to Sumida (1992), the critical value of available-soil Si content for rice growth is 300 mg SiO_2 kg^{-1}; Bollich and Matichenkov (2002) described values less than 300 mg SiO_2 kg^{-1} as deficient and values less than 600 mg SiO_2 kg^{-1} as low for rice and sugarcane (i.e. the soils might need silicate amendments). Based on these criteria, the Si contents at two sites (SW-C 11 and SW-C 15) were less than 300 mg SiO_2 kg^{-1} and the Si contents at 10 sites (SW-C 1, SW-C 2, SW-C 4, SW-C 5, SW-C 9, SW-C 10, SW-C 12, SW-C 13, SW-C 14 and SW-C 16) were less than 600 mg SiO_2 kg^{-1} in Citarum (Table 1). In Kaligarang, no sites were recorded values of less than 300 mg SiO_2 kg^{-1}, but eight sites (SW-K 3, SW-K 5, SW-K 6, SW-K 7, SW-K 10, SW-K 11, SW-K 13 and SW-K 15) had contents of less than 600 mg SiO_2 kg^{-1} (Table 2). In reference to the criterion given by Sumida (1992), some sawahs were deficient in available-soil Si for rice plant growth in Citarum and almost all sawahs were lower than the criterion of Bollich and Matichenkov (2002). The Si content in rice flag leaves at sites in the present study (Table 3) showed that seven out of 12 samples had contents of less than 125 g SiO_2 kg^{-1}, which was defined as possibly low or even critical for rice plants (Ma and Takahashi 2002). Although the critical level for available Si for rice plants varied depending on the region (Savant *et al.* 1997b), these findings suggest that deficiencies in available Si occurred in Indonesian sawah soils. This might be a reason for the recent fluctuation and stagnancy in rice productivity in Indonesia, as described by Savant *et al.* (1997a). There have been no studies on the influence of Si on rice yield and growth in Indonesia. Therefore, there is no direct evidence of Si deficiency in sawah soil in Indonesia. However, the blast disease that has been attacking rice plants and the stagnancy in rice productivity over the past decades might be an indication of the Si deficiency that has occurred in Indonesian sawah soils. According to the Indonesian Ministry of Agriculture (2005), reductions in rice yield could reach 50–90% as a result of blast disease and it has been reported that approximately 12,730 ha of sawah have been attacked by blast disease, resulting in 322 ha sawah failing to harvest in 2004.

Dynamics of Si in soils in relation to parent material and land use

We compared soil-available Si from upper to lower topographical positions with different land uses in both the Citarum and Kaligarang watersheds. In general, Si availability in soils is influenced by the type of parent material and the land use in different farming systems. Soils derived from volcanic ash contained higher Si than other parent materials, including shale, quartz, granite and peat (Imaizumi and Yoshida 1958). In the Citarum watershed, soils derived from volcanic ash and tuff volcanic were mainly distributed in upper and middle topographical positions (Table 1), while in the Kaligarang

Table 1 Characteristics of the soils and the available silica in the Citarum watershed

Sampling code†	Location	Geographical position	Land use	Altitude (m a.s.l.)	Parent material‡	pH	Total carbon (g kg^{-1})	Available silica (mg SiO_2 kg^{-1})
VC-C 1	G. Putri, Cipanas, Cianjur	S06°45′28.3″ E107°00′34.1″	Vgtb. crop	1596	Tuff intermediate	5.5 ± 0.4	24.8 ± 1.6	711 ± 295
VC-C 2	G. Putri, Cipanas, Cianjur	S06°45′32.3″ E107°00′34.1″	Vgtb. crop	1582	Tuff intermediate	5.6 ± 0.1	30.8 ± 3.6	722 ± 10
VC-C 3	Riunggunung, Pengalengan, Bandung	S07°11′04.5″ E107°33′01.4″	Vgtb. crop	1448	Ash, sand volcanic intermediate	5.6 ± 0.2	14.8 ± 0.2	1249 ± 153
VC-C 4	Riunggunung, Pengalengan, Bandung	S07°11′04.5″ E107°33′02.2″	Vgtb. crop	1441	Ash, sand volcanic intermediate	5.0 ± 0.1	11.4 ± 0.2	728 ± 191
Tea-C 1	Riunggunung, Pengalengan, Bandung	S07°11′05.3″ E107°32′58.1″	Tea plt.	1440	Ash, sand volcanic intermediate	4.5 ± 0.3	87.1 ± 15.7	370 ± 62
Tea-C 2	Riunggunung, Pengalengan, Bandung	S07°09′53.7″ E107°34′30″	Tea plt.	1438	Ash, sand volcanic intermediate	4.9 ± 0.1	73.8 ± 11.1	565 ± 285
Pine-C	Riunggunung, Pengalengan, Bandung	S07°11′24″ E107°33′02.8″	Pine plt.	1436	Ash, sand volcanic intermediate	5.7 ± 0.2	56.7 ± 1.1	1907 ± 73
VC-C 5	Riunggunung, Pengalengan, Bandung	S07°10′58.1″ E107°32′45.8″	Vgtb. crop	1421	Ash, sand volcanic intermediate	5.5 ± 0.3	17.3 ± 2.7	457 ± 57
Mz-C 1	Riunggunung, Pengalengan, Bandung	S07°10′58.9″ E107°32′45.1″	Maize crop	1416	Ash, sand volcanic intermediate	4.5 ± 0.1	13.2 ± 3.3	549 ± 54
Fl-C	Pasir muncang, Cimanggung	S06°57′39.9″ E107°52′57.6″	Fallow	1125	Tuff-volcanic intermediate	5.1 ± 0.1	33.5 ± 3.1	727 ± 16
Tob-C	Pasir muncang, Cimanggung	S06°57′38″ E107°52′59″	Tobacco	1100	Tuff-volcanic intermediate	5.6 ± 0.2	17.7 ± 7.5	639 ± 0.3
Mz-C 2	Loa, Paseh, Bandung	S07°05′02.5″ E107°47′56.4″	Maize crop	1038	Tuff-volcanic intermediate	4.6 ± 0.2	11.7 ± 1.1	423 ± 20
Mz-C 3	Loa, Paseh, Bandung	S07°05′01.5″ E107°47′55″	Maize crop	1036	Tuff-volcanic intermediate	5.1 ± 0.3	10.0 ± 2.5	982 ± 215
SW-C 1	Loa, Paseh, Bandung	S07°04′50.4″ E107°47′25.2″	Sawah	902	Tuff-volcanic intermediate	5.7 ± 0.2	42.0 ± 6.8	575 ± 81
SW-C 2	Loa, Paseh, Bandung	S07°04′49.3″ E107°47′25.7″	Sawah	894	Tuff-volcanic intermediate	6.3 ± 0.2	36.8 ± 2.1	524 ± 415
SW-C 3	Cipinang, Banjaran	S07°05′32.6″ E107°33′18.4″	Sawah	865	Tuff-volcanic intermediate	6.0 ± 0.3	39.8 ± 12.7	666 ± 157
SW-C 4	Cipalibuoy, Banjaran	S07°05′32″ E107°33′19″	Sawah	850	Tuff-volcanic intermediate	5.9 ± 0.1	17.8 ± 9.4	575 ± 142
SW-C 5	Mekar Pawitan, Bandung	S07°02′41.4″ E107°46′37.2″	Sawah	715	Material of lake sediment	6.4 ± 0.3	23.8 ± 1.1	337 ± 174
SW-C 6	Gandasari, Soreang	S07°01′08.2″ E107°32′33.7″	Sawah	710	Material of lake sediment	5.9 ± 0.5	19.2 ± 12.2	623 ± 52

Table 1 *Continued*

Sampling code†	Location	Geographical position	Land use	Altitude (m a.s.l.)	Parent material‡	pH	Total carbon (g kg^{-1})	Available silica (mg SiO_2 kg^{-1})
SW-C 7	Babakankopo, Majalaya	S07°03′52.5″ E107°45′16″	Sawah	707	Alluvio-colluvium sediment	6.0 ± 0.5	33.9 ± 1.3	632 ± 34
SW-C 8	Majasetra, Majalaya	S07°01′47.8″ E107°45′20.3″	Sawah	697	Material of lake sediment	5.4 ± 0.2	35.9 ± 6.9	609 ± 32
SW-C 9	Ramasari, Ciranjang	S06°50′55.8″ E107°18′07.6″	Sawah	322	Tuff intermediate	6.0 ± 0.1	16.0 ± 9.8	598 ± 272
SW-C 10	Sukawangi, Ciranjang	S06°50′28.6″ E107°19′30.1″	Sawah	290	Material of lake sediment	6.1 ± 0.7	26.9 ± 6.6	417 ± 20
SW-C 11	Kotapohaci, Karawang	S06°24′37.7″ E107°21′04.1″	Sawah	45	Clay sediment	5.8 ± 0.9	26.7 ± 3.1	203 ± 19
SW-C 12	Krajandesa, Rengasdengklok	S06°07′58.3″ E107°18′55.9″	Sawah	26	Clay and sand sediment	6.2 ± 0.1	13.8 ± 2.8	341 ± 50
SW-C 13	Krajandesa, Rengasdengklok	S06°07′58.3″ E107°18′55.9″	Sawah	26	Clay and sand sediment	5.9 ± 0.5	25.7 ± 6.6	405 ± 191
SW-C 14	Ampel, Karawang	S06°13′31.7″ E107°18′34.6″	Sawah	26	Accumulation of clay	6.1 ± 0.6	25.4 ± 8.1	453 ± 33
Gd-C	Kosambi, Karawang	S06°04′17.4″ E107°10′16.7″	Garden	25	Accumulation of clay	7.1 ± 0.6	10.0 ± 1.6	483 ± 22
SW-C 15	Babakanasem, Karawang	S06°03′37.7″ E107°10′51.7″	Sawah	21	Accumulation of clay	7.0 ± 0.7	13.4 ± 7.2	291 ± 95
SW-C 16	Krajan desa, Rengasdengklok	S06°05′54.3″ E107°20′02.1″	Sawah	20	Accumulation of clay and sand	5.9 ± 0.2	15.1 ± 7.3	314 ± 99

†VC, Vgtb. crop: vegetable crop; Mz, maize; Fl, fallow; Tob, tobacco; SW, sawah: a leveled and bounded rice field with an inlet and an outlet for irrigation and drainage; Gd, garden; plt, plantation; C, Citarum. ‡Indonesian Soil Research Institute soil map of the Citarum watershed (1:50.000). Values are mean ± standard deviation of soil samples at two soil depths (0–15 cm and 15–30 cm).

Table 2 Characteristics of the soils and the available silica in the Kaligarang watershed

Sampling code[†]	Location	Geographical position	Land use	Altitude (m a.s.l.)	Parent material[‡]	pH	Total carbon (g kg^{-1})	Available silica (mg SiO_2 kg^{-1})
Cof-K	Gemarang Lor, Ungaran	S07°11′11.6″ E110°22′46.8″	Coffee plt.	876	Tuff and volcanic ash	5.8 ± 0.1	17 ± 9.5	476 ± 39
Clo-K	Kalisidi, Ungaran	S07°08′46.5″ E110°21′29.9″	Clove plt.	847	Tuff and volcanic ash	5.6 ± 0.3	19.5 ± 6	520 ± 23
SW-K 1	Kalisidi, Ungaran	S07°08′06.5″ E110°21′54.6″	Sawah	704	Tuff and volcanic ash	6.4 ± 0.3	14.7 ± 2.4	723 ± 60
VC-K	Gebugan, Ungaran	S07°10′24.4″ E110°24′16.1″	Vgtb. crop	514	Breccia and tuff volcanic	5.4 ± 0.4	18 ± 10.8	434 ± 268
SW-K 2	Branjang, Semarang	S07°07′17.7″ E110°21′05.1″	Sawah	457	Tuff and volcanic ash	6.0 ± 0.1	24.9 ± 1.1	628 ± 43
SW-K 3	Langensari timur, Candirejo	S07°10′02.8″ E110°24′16.3″	Sawah	453	Breccia and tuff volcanic	5.6 ± 0.2	17 ± 7.3	463 ± 135
SW-K 4	Lerep, Gn.Pati, Semarang	S07°06′49.5″ E110°23′37.9″	Sawah	337	Tuff volcanic	7.5 ± 0.2	15.4 ± 2.7	915 ± 220
SW-K 5	Lerep, Gn.Pati, Semarang	S07°07′01″ E110°24′02.5″	Sawah	319	Tuff volcanic	6.2 ± 0.2	18.9 ± 5.2	414 ± 35
SW-K 6	Lerep, Gn.Pati, Semarang	S07°07′12.6″ E110°24′02.8″	Sawah	304	Tuff volcanic	6.1 ± 0.1	11.5 ± 4.8	529 ± 46
SW-K 7	Bentul, Polaman, Ungaran	S07°05′09.5″ E110°20′39.7″	Sawah	262	Breccia and tuff volcanic	6.5 ± 0.1	18 ± 0.8	391 ± 81
SW-K 8	Bentul, Polaman, Ungaran	S07°05′06.1″ E110°20′35.1″	Sawah	261	Tuff volcanic	6.3 ± 0.4	11.6 ± 2	714 ± 129
SW-K 9	Delok, Banjarejo, Semarang	S07°05′13.7″ E110°20′27.1″	Sawah	255	Tuff and volcanic ash	5.5 ± 0.1	16.7 ± 4.8	1020 ± 27
SW-K 10	Banjarejo, Gn.Pati, Semarang	S07°05′13.1″ E110°20′30.5″	Sawah	253	Tuff and volcanic ash	5.7 ± 0.2	10.9 ± 0.8	497 ± 49
SW-K 11	Gilisari, Polaman, Ungaran	S07°05′13.1″ E110°20′32.5″	Sawah	248	Tuff and volcanic ash	6.4 ± 0.6	13.9 ± 1.7	512 ± 77
Rub-K	Kedung Pane, Ungaran	S07°02′05.3″ E110°20′11″	Rubber plt.	223	Tuff volcanic	6.1 ± 0.1	11.9 ± 0.3	559 ± 21
SW-K 12	Banjarejo, Semarang	S07°05′15″ E110°20′31.1″	Sawah	251	Tuff and volcanic ash	6.2 ± 0.9	15 ± 6.4	810 ± 5
SW-K 13	Talunkacang, Semarang	S07°02′22.7″ E110°20′54.7″	Sawah	65	Tuff and volcanic ash	5.8 ± 0.3	19.8 ± 3	466 ± 9
SW-K 14	Manyaran, Sadeng	S07°01′13″ E110°22′28.7″	Sawah	65	Sandstone and limestone	6.5 ± 0.2	22.6 ± 0.5	673 ± 6
SW-K 15	Tambakharjo, Semarang	S06°58′44.7″ E110°21′52″	Sawah	24	Breccia and tuff volcanic	6.8 ± 0.3	23.8 ± 5.2	418 ± 71

[†]Cof, coffee; Clo, clove; SW, sawah: a leveled and bounded rice field with an inlet and an outlet for irrigation and drainage; VC, Vgtb crop: vegetable crop; Rub, rubber; K, Kaligarang. [‡]Indonesian Soil Research Institute map of Central Java (1:50.000). Values are mean ± standard deviation of soil samples at two soil depths (0–15 cm and 15–30 cm).

Table 3 Silica (Si) content in rice flag leaves and the available Si in soils of some selected sawah in the Citarum and Kaligarang watersheds

Code†	Rice variety	Si in flag leaves ($g\ SiO_2\ kg^{-1}$)	Available Si in soil ($mg\ SiO_2\ kg^{-1}$)
Citarum			
SW-C 2	Ciasem‡	135.19	524 ± 415
SW-C 3	IR 64	170.45	666 ± 157
SW-C 4	IR 64	101.13	575 ± 142
SW-C 8	IR 64	84.71	609 ± 32
SW-C 12	Ciherang‡	57.28	341 ± 50
SW-C 16	Memberamo‡	58.49	314 ± 99
Kaligarang			
SW-K 3	IR 64	103.96	465 ± 135
SW-K 5	Way apo buru‡	189.88	414 ± 35
SW-K 6	IR 64	178.41	529 ± 46
SW-K 7	IR 64	80.67	391 ± 81
SW-K 10	IR 64	136.65	497 ± 49
SW-K 13	IR 64	85.52	466 ± 9

†SW, sawah: a leveled and bounded rice field with an inlet and an outlet for irrigation and drainage; C, Citarum; K, Kaligarang. ‡Local name. Values are mean ± standard deviation of soil samples at two soil depths (0–15 cm and 15–30 cm).

watershed tuff and volcanic ash were distributed from upper to lower topographical positions (Table 2). In the Citarum watershed, the content of soil-available Si in the upper and middle topographical positions derived from the parent materials of volcanic ash and tuff volcanic tended to be higher than the contents in lower topographical positions derived from the parent materials of lake sediment and clay accumulation. However, such a trend was not found in the Kaligarang watershed, where the parent materials were rather similar in the watershed (Table 2).

Aside from parental material differences, available Si content in the soils of the Citarum watershed varied depending on land-use type (Table 1). In upper and middle topographical positions in the Citarum watershed, where parent materials were similar, when we compared the available Si content in the soil of respective land uses, except sawah, the highest value was found in a pine plantation, 1,907 $mg\ SiO_2\ kg^{-1}$, and the lowest value was found in a tea plantation, 370 $mg\ SiO_2\ kg^{-1}$. Available Si in the surface soil of the pine plantation, which was established more than 30 years ago, probably accumulated as biogenic Si with its TC of 56.7 $g\ kg^{-1}$ through high Si uptake and return by pine trees (Table 1); Markewitz and Richter (1998) found the accumulation of Si aboveground in a loblolly pine forest to be 89.9 $kg\ ha^{-1}\ year^{-1}$. Although common biogenic Si is not easily dissolved in water, Alexander *et al.* (1997) reported that dissolution of phytolith occurred in the rainforest and recorded approximately 54 ± 5 to 70 ± 7 $kg\ ha^{-1}\ year^{-1}$. This same mechanism might increase the available Si in the pine plantation. In contrast, soil-available Si in the tea plantation was relatively low. Soil pH in the tea plantations was low (4.5 and 4.9). Acidification probably occurred as a result of heavy urea application, which reached 350 $kg\ N\ ha^{-1}\ year^{-1}$ (Husnain, pers. comm. with local farmers, 2005), and possibly enhanced Si loss through leaching. Soils in the maize crop fields of Mz-C 1 and Mz-C 2 also had low pH values (4.5 and 4.6) and contained relatively little available Si in the soil (Table 1). Land used for vegetable crops, fallow and tobacco had relatively high soil-available Si, while intensive farming systems might enhance depletion of soil-available Si (e.g. VC-C 5, Mz-C 1 and Mz-C 2). These results suggest that the types of land use in different farming systems, including crop types and fertilization, also influenced Si availability in the soils in upper and middle topographical positions of the Citarum watershed. The content of available Si in sawah soils in Citarum ranged from 203 to 666 $mg\ SiO_2\ kg^{-1}$. The sawahs in the Citarum watershed are distributed in the middle to lower parts and generally show lower soil-available Si contents than other land-use types in the upper to middle parts, possibly because of differences in the parent materials. In particular, soils of sawah developed from the accumulation of lake and sediment materials had low contents of Si, and this has reported for some alluvium soils (Holmes 1939; Huang *et al.* 2006). In Kaligarang, available Si content in the sawah ranged from 391 to 1,020 $mg\ SiO_2\ kg^{-1}$ and in coffee, clove and rubber

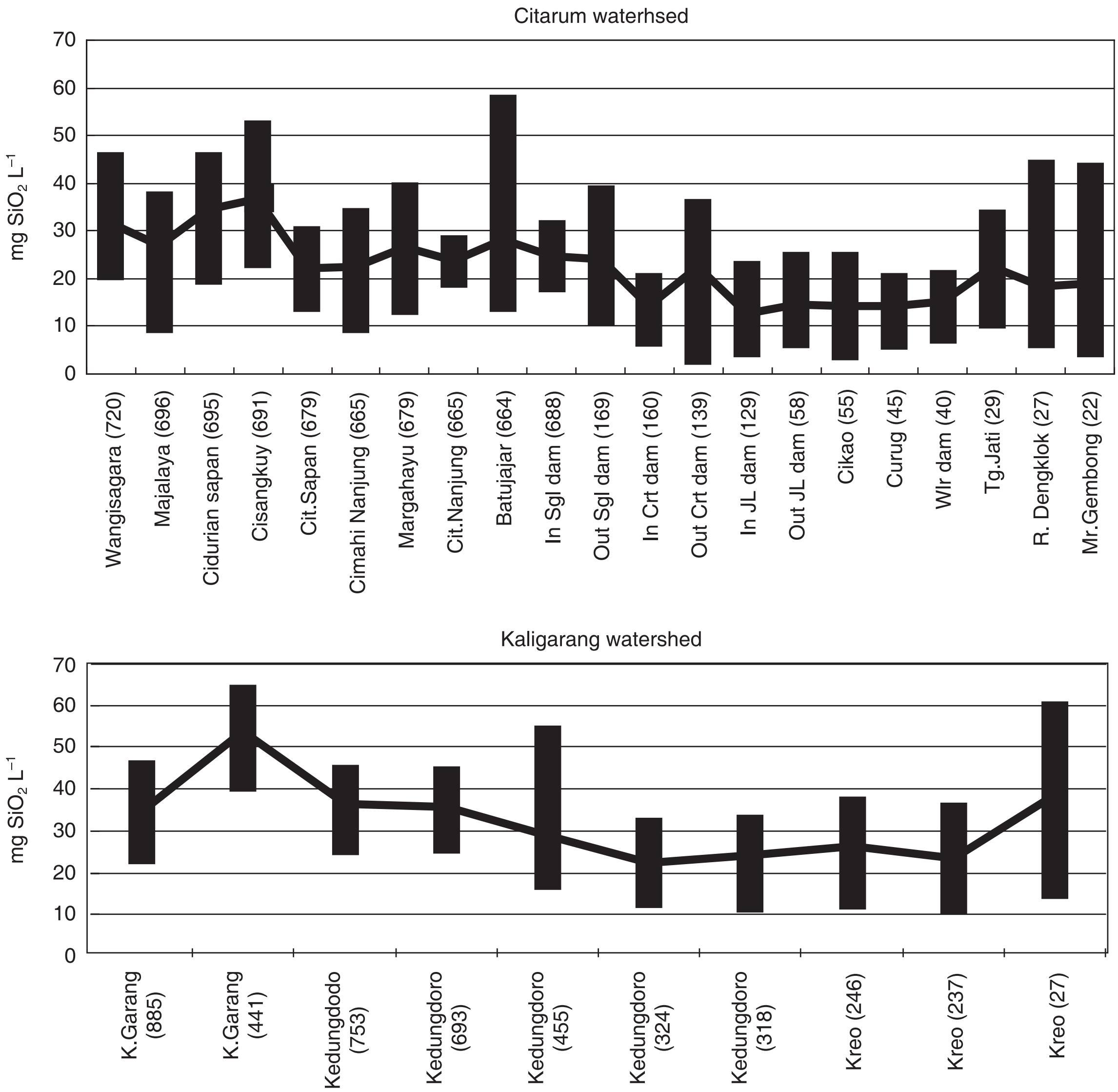

Figure 2 Silica concentration of the upper to lower stream of the Citarum and Kaligarang Rivers from September 2006 to November 2007. Cit, Citarum; In, Inlet; Out, Outlet; Sgl dam, Saguling dam; Crt dam, Cirata dam; Jl dam, Jatiluhur dam; Wlr dam, Walahar dam. Numbers in parentheses indicate altitude (m a.s.l.).

plantations it was approximately 476, 520 and 559 mg SiO_2 kg^{-1}, respectively. Available Si content did not obviously change according to land-use type, probably because there was no site that showed very high TC accumulation and low pH as seen in the Citarum watershed. In sawah soils, high Si uptake by rice plants and straw handling might have influenced the available Si contents; Darmawan *et al.* (2006) reported that the available Si contents in sawah soils on Java Island have decreased in the past three decades. However, differences in parent materials appear to be the major factor influencing Si availability in soils at the watershed scale.

Concentration of Si in river and irrigation canal water

Concentrations of Si from the upper to lower stream of a river in Citarum and Kaligarang are shown in Fig. 2. In Citarum, the average Si concentration in the upper stream ranged from 22.2 to 36.6 mg SiO_2 L^{-1}, while in the middle and lower stream it ranged from 12.6 to 24.8 mg SiO_2 L^{-1}. In Kaligarang, the average Si concentration in the upper stream ranged from 34.4 to 53.7 mg SiO_2 L^{-1} and in the middle and lower stream it ranged from 22.5 to 38.5 mg SiO_2 L^{-1}. This result shows that, in general, the Si concentration in Citarum is lower than that in Kaligarang. The geological condition of the watersheds appears to affect this difference. Kawaguchi and Kyuma (1977) summarized that the Si content in rivers under geological conditions of volcanic ash is higher than that of marl, lime and acid tuff loam on Java Island, of which the average Si content was 42.3 mg SiO_2 L^{-1}, 30.2 mg SiO_2 L^{-1}, 18.2 mg SiO_2 L^{-1} and 28.6 mg SiO_2 L^{-1}, respectively. Ma and Takahashi (2002) stated that the Si content is higher in volcanic ash than in granite and sedimentary rocks by three–fourfold. In Kaligarang, where relatively high Si contents were found in the rivers, volcanic ash was distributed from the upper to lower stream (Table 2), while in Citarum it was mainly present only upstream. By comparison, the content of Si in irrigation water in other Asian countries, as summarized by Kawaguchi and Kyuma (1977), ranged from 10.1 to 23.7 mg SiO_2 L^{-1}, from 5.3 to 16.3 mg SiO_2 L^{-1} and from 7.3 to 21.8 mg SiO_2 L^{-1} in Thailand, West Malaysia and Sri Lanka, respectively. The range of Si contents in the river and canal water in the present study is comparable to that found in these Asian countries.

Instead of geological factors, Si concentration in irrigation water appears to be influenced by the depletion of Si in dams. As shown in Fig. 2, the Si concentration in the Citarum River was depleted by 49–58% in dams that flow from the outlet of the Saguling dam, the outlet of the Cirata dam, the inlet and outlet of the Jatiluhur dam and from other small dams, including the Curug and Walahar dams. The Jatiluhur dam is supplying water for irrigated sawah along the Citarum watershed. Therefore, when the Si content in the river or canal water is decreased at the dam, the supply of Si to the sawah also decreases. A wide range of Si concentrations were found in the lower stream of Citarum; however, we could not clarify the reason in the present study by checking seasonal fluctuations in Si concentration in relation to precipitation. This decreasing trend was not found in Kaligarang, possibly because no dam exists. It has been reported that Si retention in a dam occurs because of an increase in algal populations, which are affected by high inputs of nutrients such as nitrogen and phosphorus (Humborg *et al.* 2000). According to Reynolds (1984), diatoms require Si to construct their cell walls (frustules) and the Si content can be as high as 26–69% of the dry weight of their cells. Silica trapping by an algal bloom resulting from anthropogenic phosphorus input in Lake Biwa in the 1970s was reported by Harashima (2003). In the Citarum watershed, this type of Si trap in dams that were constructed after the 1960s has probably occurred. Detailed results of an Si trap in a dam in the Citarum watershed will be presented in a subsequent paper.

In addition to the present Si dynamics in these watersheds, there have been a number of reports examining long-term changes in Si availability in water and soils. Weathering processes enhance dessilication and affect Si content in river and canal water. Depletion of Si content in river and canal water has been investigated. In Yamagata prefecture, Japan, from 1956 to 1996, the Si concentration in irrigation water decreased by 21.2–23.3 mg SiO_2 L^{-1} (Kumagai *et al.* 1998).

The results obtained in the present study suggest that the Si availability in the soil and water in two watersheds in Java is mainly influenced by the parent material. In addition, the type of land use affected soil Si availability in the watersheds. Twelve sawah sites out of 16 in Citarum and nine sawahs out of 15 are classified as low or deficient in available Si contents for rice plant growth. In particular, sawah sites located in the lower part of the Citarum watershed, where the parent materials consist of the accumulation of lake and clay sediments, contain relatively little available Si. Furthermore, the Si contents of the rivers and canals were depleted in dams in the Citarum watershed. This low Si availability in soils and irrigation water possibly has an influence on rice growth and productivity in these watersheds, although we have had no research data on the relationships between Si availability and rice growth and productivity in Java. It might be time to start considering how to manage and compensate available Si in sawah in Java, Indonesia.

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