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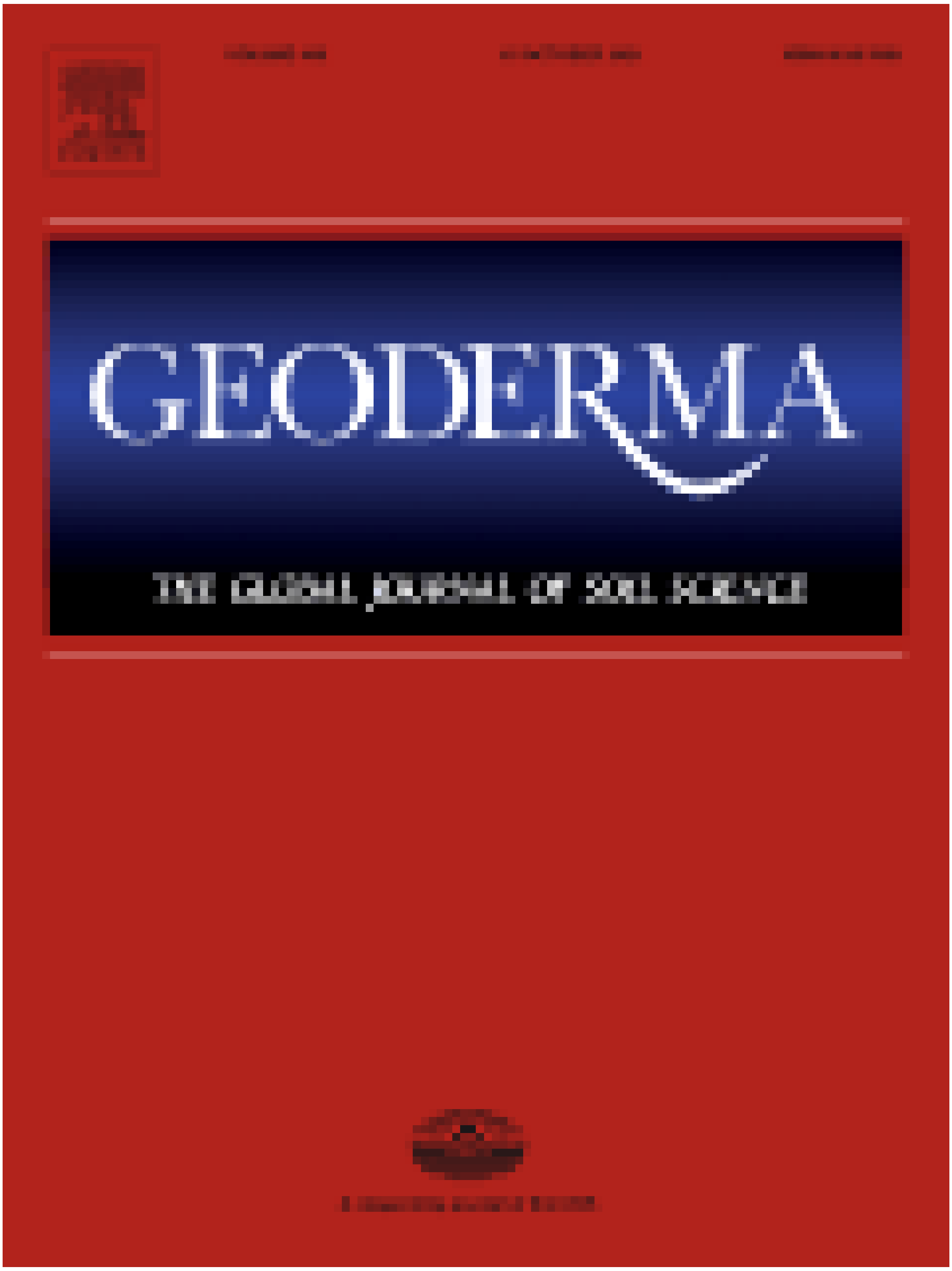

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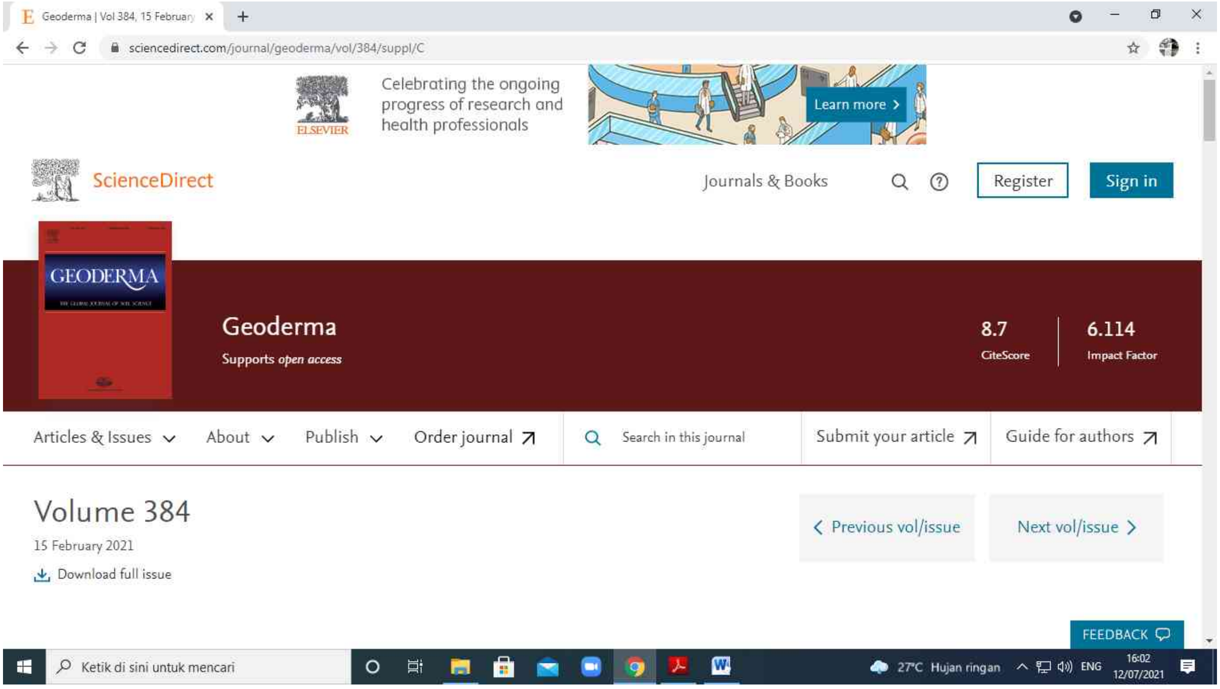

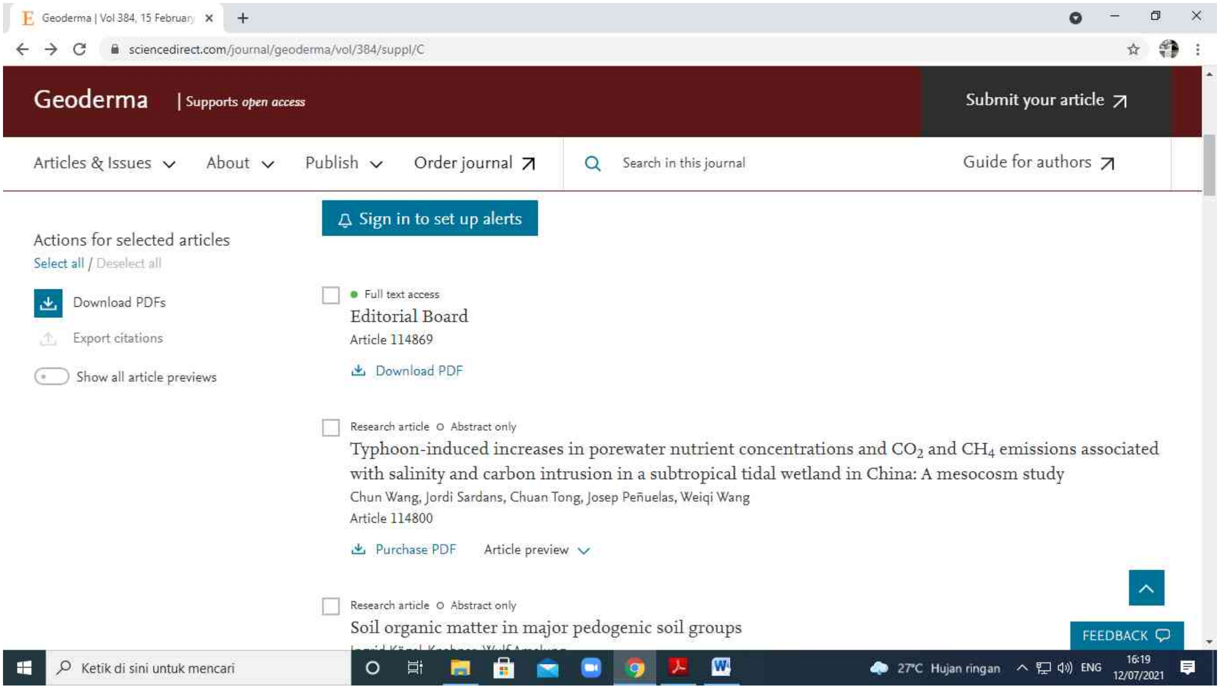

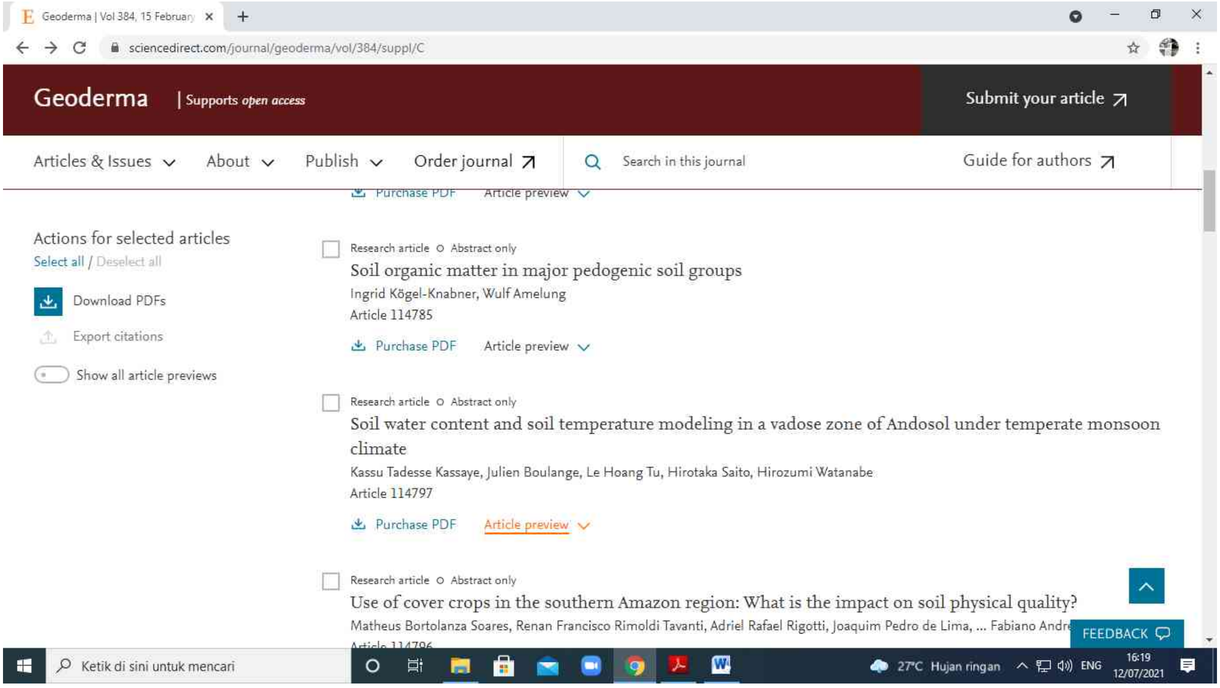
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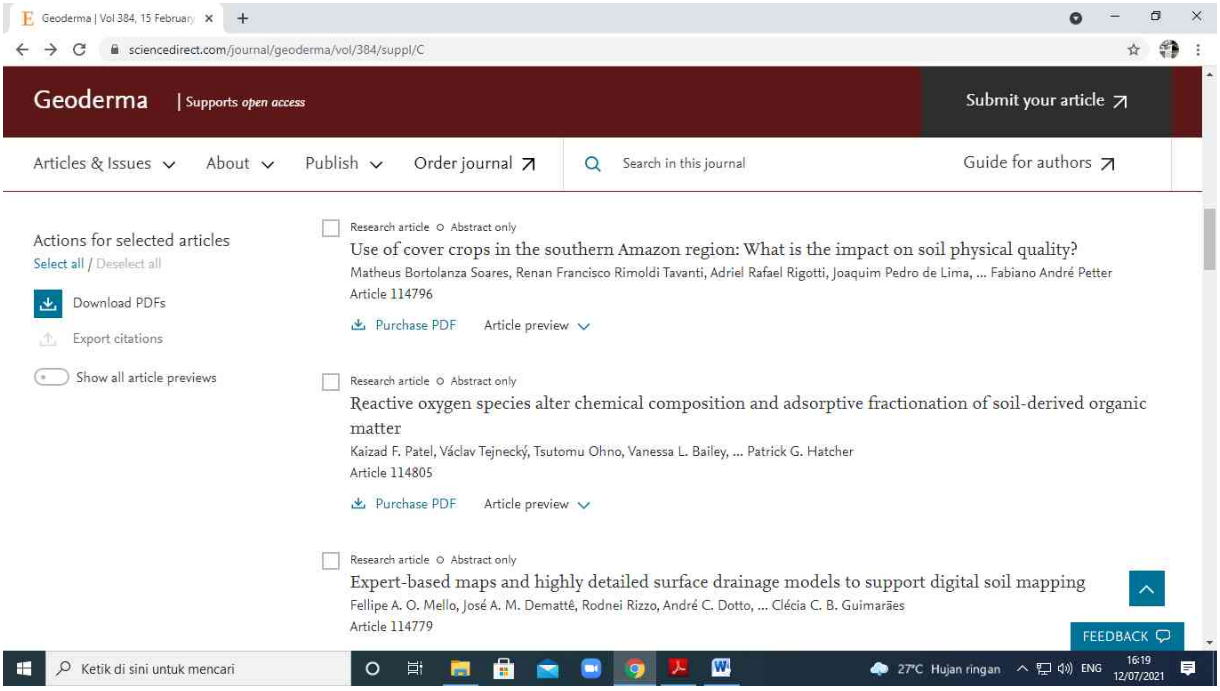
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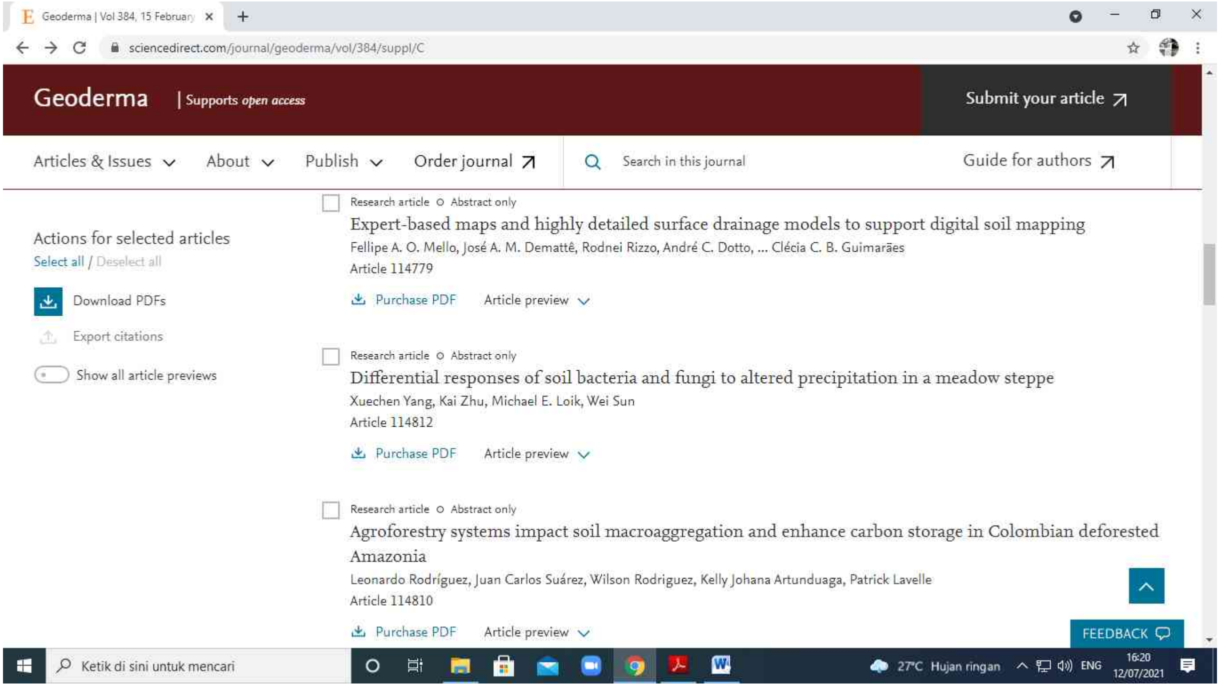

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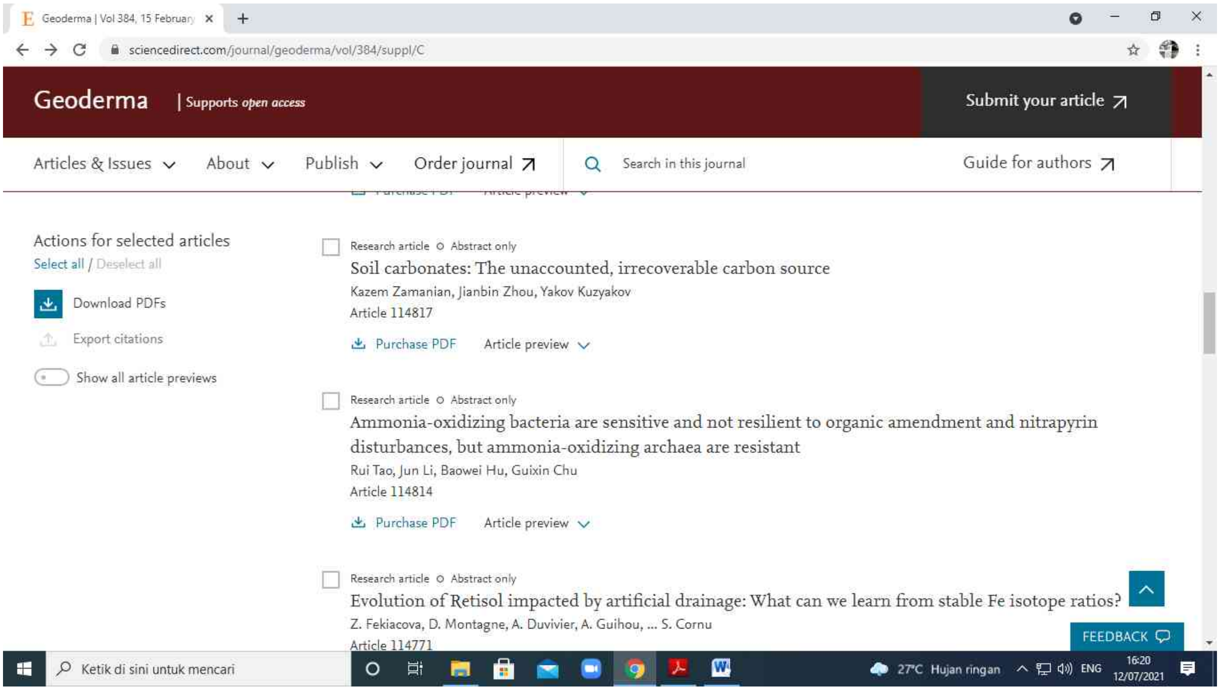

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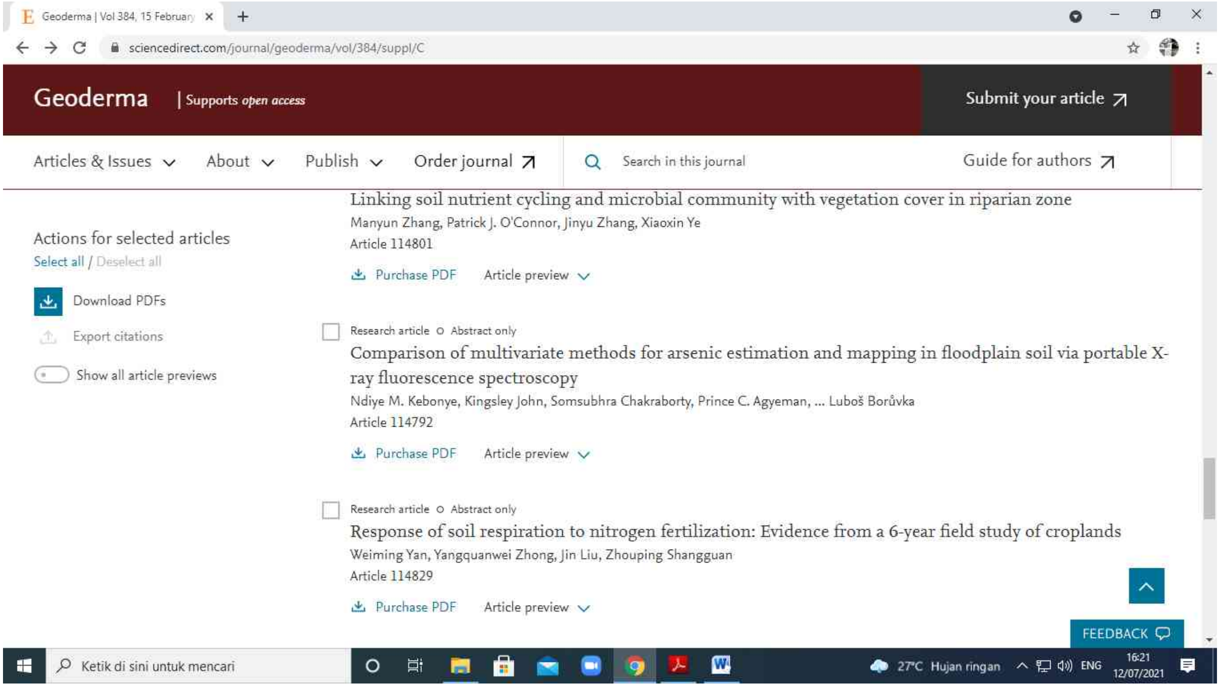
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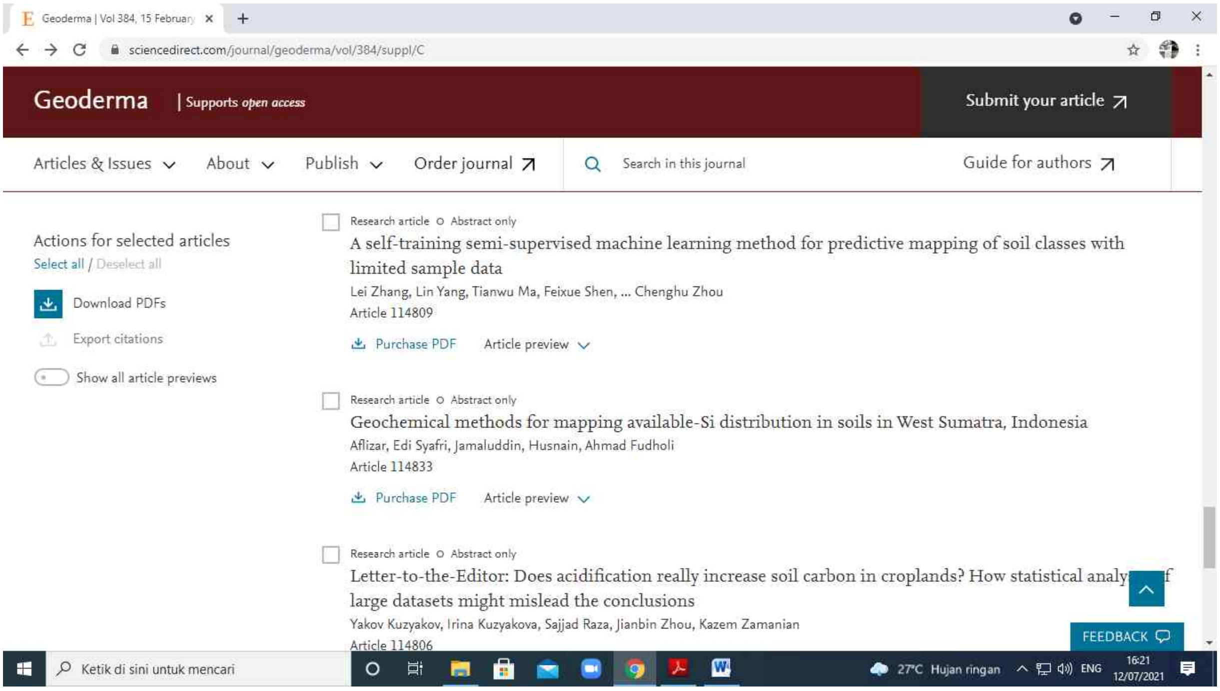
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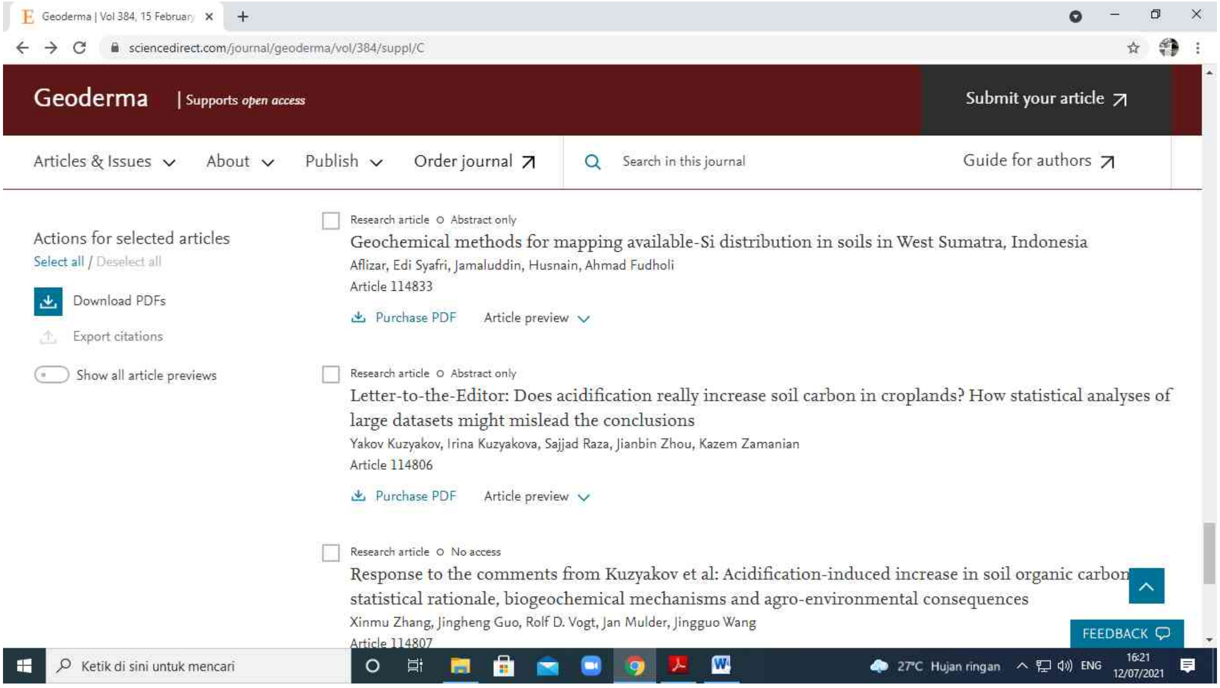
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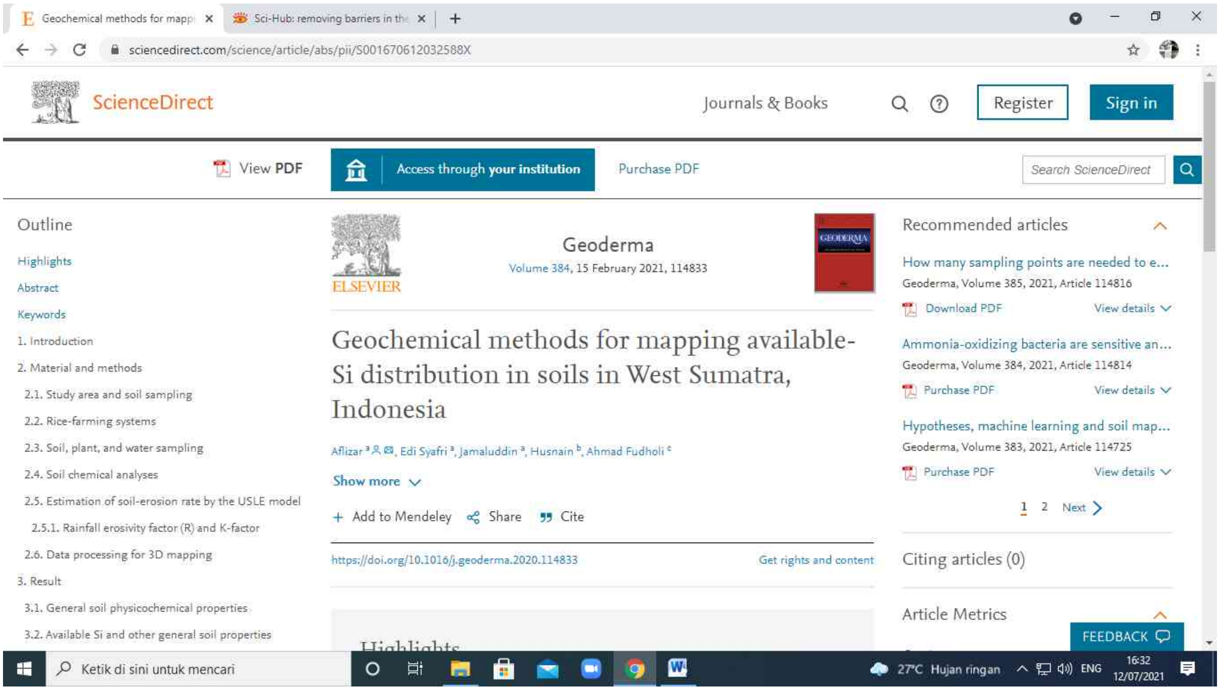
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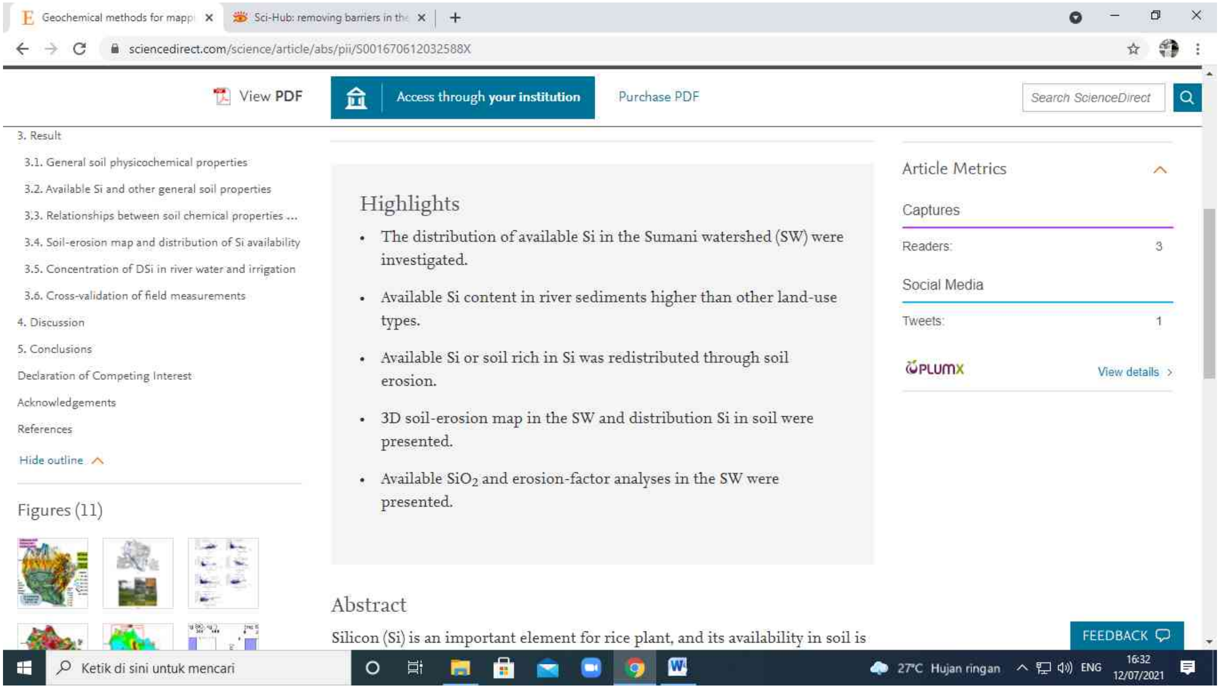

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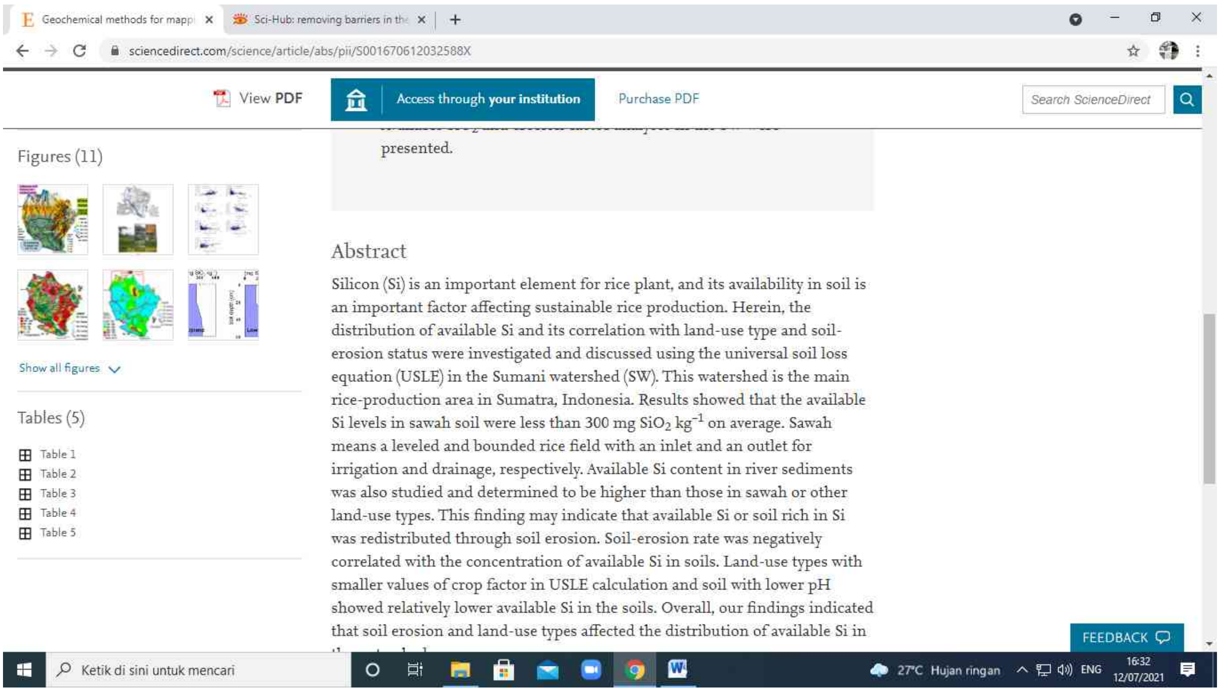
Highlights

- The distribution of available Si in the Sumani watershed (SW) were investigated.
- Available Si content in river sediments higher than other land-use types.
- Available Si or soil rich in Si was redistributed through soil erosion.
- 3D soil-erosion map in the SW and distribution Si in soil were presented.
- Available SiO_2 and erosion-factor analyses in the SW were presented.

Abstract

Silicon (Si) is an important element for rice plant, and its availability in soil is



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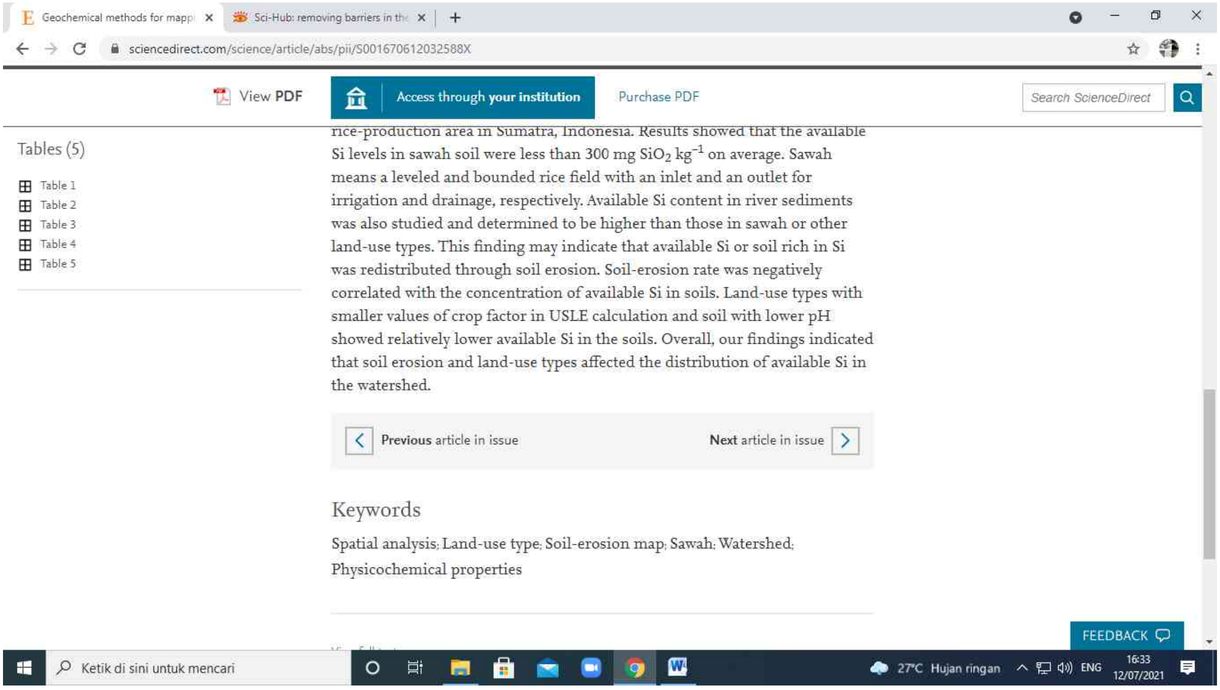
Abstract

Silicon (Si) is an important element for rice plant, and its availability in soil is an important factor affecting sustainable rice production. Herein, the distribution of available Si and its correlation with land-use type and soil-erosion status were investigated and discussed using the universal soil loss equation (USLE) in the Sumani watershed (SW). This watershed is the main rice-production area in Sumatra, Indonesia. Results showed that the available Si levels in sawah soil were less than 300 mg SiO_2 kg^{-1} on average. Sawah means a leveled and bounded rice field with an inlet and an outlet for irrigation and drainage, respectively. Available Si content in river sediments was also studied and determined to be higher than those in sawah or other land-use types. This finding may indicate that available Si or soil rich in Si was redistributed through soil erosion. Soil-erosion rate was negatively correlated with the concentration of available Si in soils. Land-use types with smaller values of crop factor in USLE calculation and soil with lower pH showed relatively lower available Si in the soils. Overall, our findings indicated that soil erosion and land-use types affected the distribution of available Si in



rice-production area in Sumatra, Indonesia. Results showed that the available Si levels in sawah soil were less than 300 mg SiO_2 kg^{-1} on average. Sawah means a leveled and bounded rice field with an inlet and an outlet for irrigation and drainage, respectively. Available Si content in river sediments was also studied and determined to be higher than those in sawah or other land-use types. This finding may indicate that available Si or soil rich in Si was redistributed through soil erosion. Soil-erosion rate was negatively correlated with the concentration of available Si in soils. Land-use types with smaller values of crop factor in USLE calculation and soil with lower pH showed relatively lower available Si in the soils. Overall, our findings indicated that soil erosion and land-use types affected the distribution of available Si in the watershed.

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Keywords

Spatial analysis; Land-use type; Soil-erosion map; Sawah; Watershed; Physicochemical properties

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Geochemical methods for mapping available-Si distribution in soils in West Sumatra, Indonesia

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ABSTRACT

Silicon (Si) is an important element for rice plant, and its availability in soil is an important factor affecting sustainable rice production. Herein, the distribution of available Si and its correlation with land-use type and soil-erosion status were investigated and discussed using the universal soil loss equation (USLE) in the Sumani watershed (SW). This watershed is the main rice-production area in Sumatra, Indonesia. Results showed that the available Si levels in sawah soil were less than 300 mg SiO_2 kg^{-1} on average. Sawah means a leveled and bounded rice field with an inlet and an outlet for irrigation and drainage, respectively. Available Si content in river sediments was also studied and determined to be higher than those in sawah or other land-use types. This finding may indicate that available Si or soil rich in Si was redistributed through soil erosion. Soil-erosion rate was negatively correlated with the concentration of available Si in soils. Land-use types with smaller values of crop factor in USLE calculation and soil with lower pH showed relatively lower available Si in the soils. Overall, our findings indicated that soil erosion and land-use types affected the distribution of available Si in the watershed.

1. Introduction

Silicon (Si) is an important element for rice production (Imaizumi and Yoshida, 1958). However, it is not a concern and has never been applied in sawah in Indonesia. In the field, blast diseases affect local rice varieties, which may be due to the deficiency of available Si, and several studies regarding the Si effect on rice production has been published in Indonesia. Darmawan et al. (2006) reported that about 11%–20% of available Si decreases in sawah soil owing to intensive rice cultivation over the last three decades. In addition, Husnain et al. (2008) reported that in West Java, the supply of Si in lowland sawah through irrigation has decreased because dissolved Si (DSi) is trapped by diatoms (phytoplankton) in dams. However, few studies have focused on the influence of Si availability on rice production and improving Si management.

To mitigate the above problems and thus improve the land-management planning of the watershed, soil erosion must be reduced. To realize this, the present status of soil erosion in relation to land-use pattern in the watershed needs to be evaluated. However, directly determining the soil erosion of the entire watershed is impractical as the necessary measurements are too broad ranging and time consuming. Estimating soil erosion using models is more common and practical. Several types of models for the estimation of soil erosion have been developed, and they include the universal soil-loss equation (Ahmadi et al., 2006; Amore et al., 2004; Moehansyah et al., 2004; Walling et al., 2003; Kusumandari and Mitchell, 1997). In general, no single best model exists for all applications. Thus, the most appropriate model depends on the purpose of the study and the characteristic of the watershed (Shamshad et al., 2008). The application of USLE was evaluated to be sufficient for estimating soil-erosion rates as it can exhibit a relative ranking of soil-loss risk in watersheds when accurate parameter values are used. The USLE has also been used as a conservation-evaluation tool in Indonesia as aforementioned, although few studies have focused on measuring or estimation soil erosion (Aflizar and Masunaga, 2013).

The distribution of silica (silicon dioxide, SiO_2) in soils is influenced by parent material, climate, vegetation, texture, pedogenesis, intensity of weathering (Hallmark and Wilding, 1982), and soil-erosion factor (Aflizar et al., 2018). The SiO_2 source for rice plant was derived from soil, irrigation water, and plant residue such as straw and rice husk if they are incorporated into the soil after harvesting. Soils derived from ash volcanic parent material contain more SiO_2 (Imaizumi & Yoshida,

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1958) than do soils derived from alluvium material, particularly those in lowlands. Many rice fields or sawah located in lowlands has parent materials that are mostly river sediment or alluvium, so the original SiO_2 availability is generally low (Aflizar et al., 2019). Rice is a typical Si-accumulator plant that takes up Si from soil solution through an active mechanism (Ma et al., 2001, 2007).

According to Wu et al. (2009), the solubility of Si is influenced by pH and iron (Fe). Soil physical properties (texture, clay percentage, silt and sand) and soil chemical properties (pH, total carbon (TC), total nitrogen (TN), calcium (Ca), magnesium, potassium (K) and sodium (Na)) are used for sustainable land management in agriculture (Hartemink, 1998). Wang et al. (2009) reported that the distribution patterns of TN, total phosphorus (TP) and other nutrients significantly change with changes in land use, and distribution maps can be used to develop sustainable agriculture and improve the environment. Aflizar et al. (2018) reported that the distribution of trace metal cadmium on a watershed is influenced by soil properties including pH, texture, TC, erosion and topographic factors.

The Indonesian government does not believe and does not acknowledge that silica (Si) deficiency has occurred in paddy soils in the country (Husnain et al., 2018; Darmawan et al., 2006). However, we hypothesise that there is an Si deficiency in the soil, especially in the Sumani watershed (SW). Thus, the conditions of rice fields in Indonesia should be evaluated. Soil erosion is considered only as a carrier of adverse effects on the environment because it causes soil degradation and disasters for the environment and agriculture (Aflizar et al., 2010). We hypothesise that soil erosion also has a good effect on the environment because it carries nutrient-rich soil sediments and precipitates them in lowland rice fields.

Many farmers and agricultural practitioners in Indonesia assume that soil Si is not necessary for paddy sawah, so they believe that adding Si in artificial fertiliser is not necessary (Husnain et al., 2018; Darmawan et al., 2006). Moreover, the soil can sufficiently provide natural Si. We hypothesise that Si in the soil is no longer sufficient for paddy sawah and that Si is contributed from irrigation water, river water (Somura et al., 2006) and sediments, which is then naturally distributed to the sawah. However, the content of Si is no longer sufficient; therefore, Si should be added in the form of fertiliser to the sawah soil.

The present study aimed to determine the factors influencing the distribution of available Si in the SW, where volcanic ash and Si fertiliser of irrigation water can be natural sources. We hypothesise that the pH, TC, TN, base cation (Ca, K, Na) and trace metal Fe are factors controlling Si availability in sawah soil. Accordingly, we conducted a study on the distribution of available Si in relation to land-use types and soil-erosion status in the SW, a main rice-production area in West Sumatra, Indonesia. We have already previously observed that severe erosion occurred in the highlands of the watershed because of the land-use change from forest to agricultural field. Accordingly, we expected that these factors may influence available-Si distribution in the watershed. Soil erosion is generally regarded as a type of soil degradation. However, it may contribute to nutrient replenishment in sawah, especially in the lowlands, through the deposition of fine soil particles eroded from the highlands, as we discuss in this study.

2. Material and methods

2.1. Study area and soil sampling

This research was conducted in the SW in the Solok regency of West Sumatra (latitude 00° 36′ 08″ to 10° 44′ 08″ S, longitude 100° 24′ 11″ to 101° 15′ 48″ E). SW has an active volcano, Mount Talang (2500 m asl). Further information about the study area and sample locations are shown in Figs. 1 and 2. On the east side of Mount Talang, we found a lake from which water flows through the lowlands and into lake Singkarak located at an altitude of 300 m asl. All the water of rivers and tributaries that flow into the SW also drain into lake Singkarak. According to data of climatological stations from 1996 to 2000. The SW has a humid tropical climate. The rainfall rate hovers at around 1669 and 3230 mm between altitudes of 300 and 2500 m. Annual temperatures range from 19 °C to 30 °C varying from highlands to lowlands. The average annual humidity also varies from 78.1% to 89.4% (Farida et al., 2005).

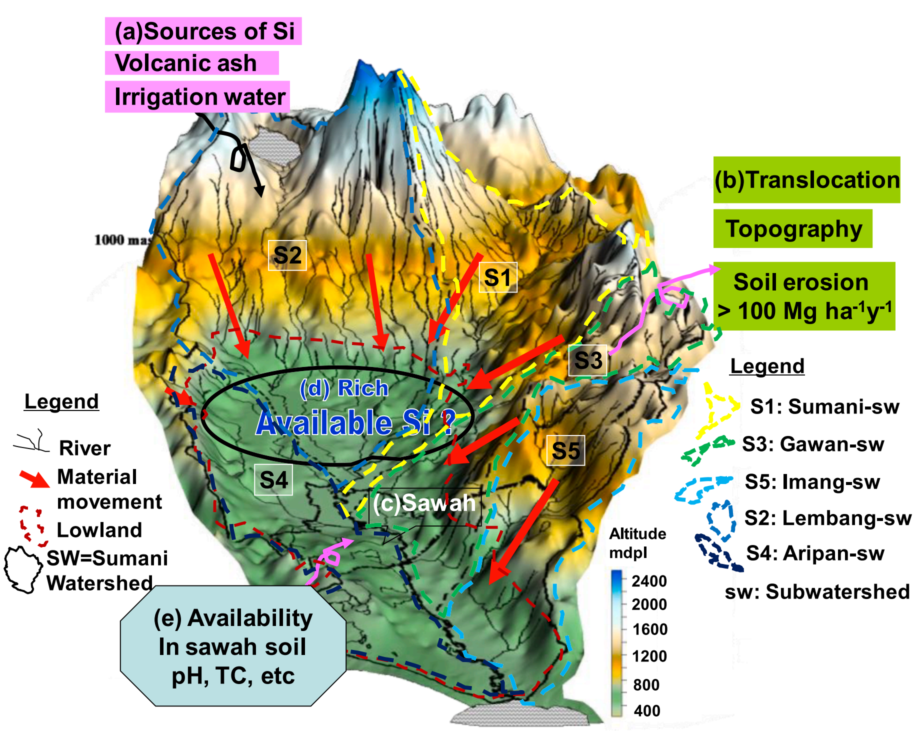

Fig. 1. Possible factors influencing the distribution of available Si in the SW. (a) Natural source of Si by volcanic ash, irrigation water and top soil. (b) Translocation of Si by topography and soil erosion. (c) Deficiency of Si in sawah soil. (d) Rich available Si in lowland. (e) Available Si in sawah soil controlled by pH, TC, etc.

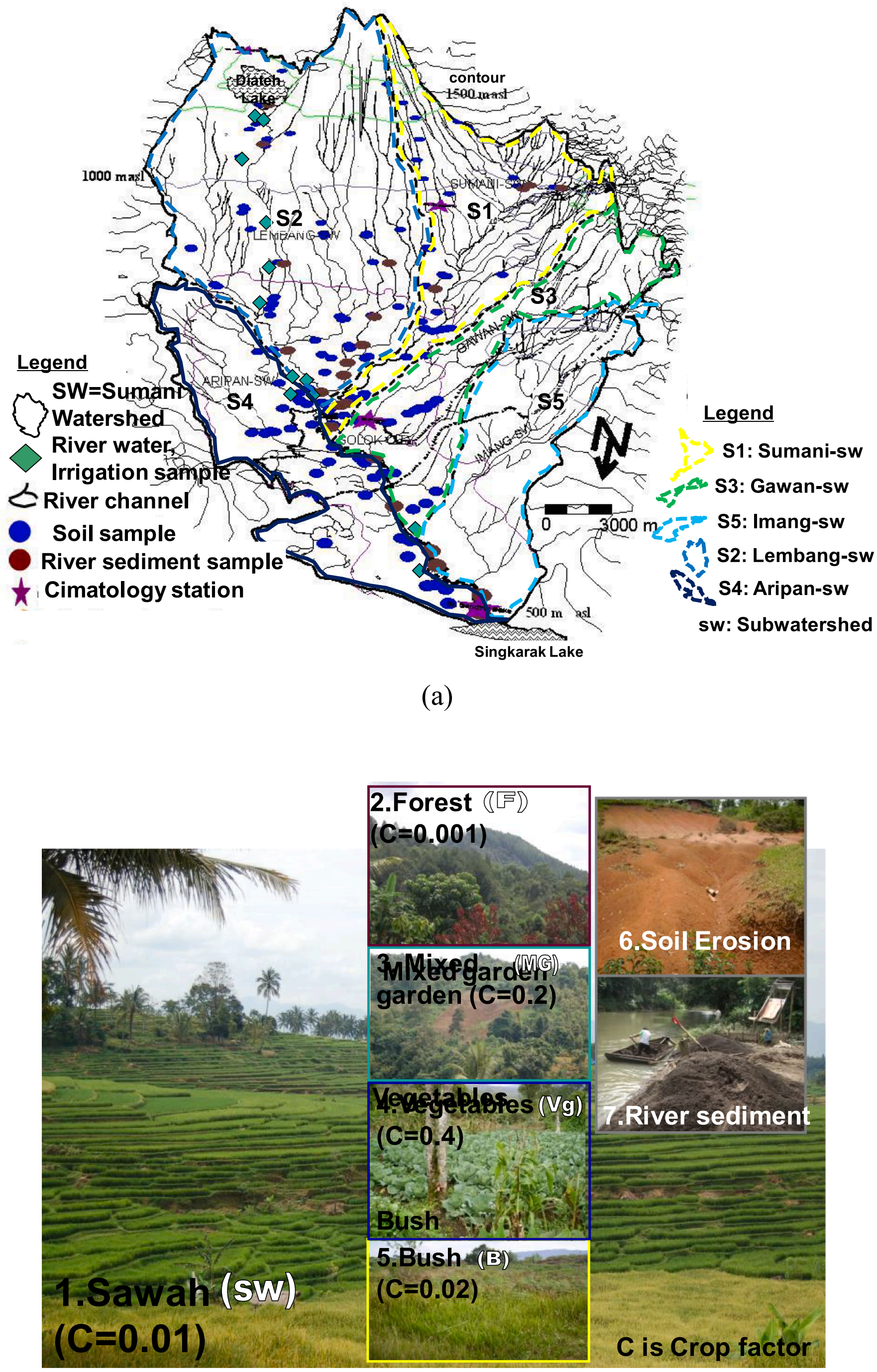

Fig. 2. Sampling point (a) and land-use type (b) in the SW: field survey picture from: 1. sawah, 2. forest, 3. mixed garden, 4. vegetables, 5. bush, 6. soil erosion, 7. river sediment.

We selected the SW for our research because of three reasons. First, we already have a database of its soil erosion. Second, the SW has various land-use types (rice fields, forests, mixed garden, garden vegetables, weeds, and bush) suitable for our research (Fig. 2b). Third, this watershed is the central of rice-production area in West Sumatra. Fig. 2a shows the soil sampling in the blue circle. The red circle represents the river-sediment sampling point. We present available Si in soil and collected soil samples from all land-use and soil types and topographical position of the various positions (Fig. 2). A total of 23 soil samples were collected from stream sediments from the highlands to the lowlands. Soil samples were taken at depths of 0–20 cm and 20–40 cm. To view the distribution of soil vertically on highlands and lowland areas, soil samples were taken at a representative area to a depth of 100 cm.

The watershed is divided into eight geology types, i.e., brecia andesit of Mt. Talang, alluvium of andesit volcano, lava, colluvial deposit, welded tuff, quartz, slate shale part of tuhur form, and lava andesit to basalt (Farida et al., 2005). SW consists of five subwatersheds, namely, Sumani (S1), Lembang (S2), Gawan (S3), Aripan (S4), and Imang (S5) (Aflizar et al., 2018).

Located in the SW is the active volcano Mount Talang. Farmers believe that this volcano enriches the soil through its frequent small eruptions and volcanic ash spread on agricultural land throughout the SW. According to Fiantis et al. (2010), the element contents of volcanic ash are SiO_2 (57.61%), Al_2O_3 (16.16%), H_2O^+ (6.92%), Fe_2O_3 (5.39%), CaO (4.79%), Na2O (2.51%), MgO (1.88%), K_2O (1.84%), H_2O^- (1.62%), TiO_2 (0.67%), P_2O_5 (0.18%), and MnO (0.08%).

On 12 April 2005, Mount Talang erupted and ejected ash into the air that then fell and spread throughout the SW. The volcanic ash covered the summit and slopes of Mount Talang with a thickness of 5 and 0.1 cm, respectively, around the foot of Mount Talang. Fiantis et al. (2010) reported that the chemical characteristics of volcanic ash from Mount Talang are as follows: pH H_2O (1:5)(7.26), pH KCl (1:5)(7.12), P Bray 2 (68.02 mg kg^{-1}), P HCl 25% (498.12 mg kg^{-1}), CEC (5.75 cmolc(+) kg^{-1}), Ca (11.14 cmolc(+) kg^{-1}), Mg (2.18 cmolc(+) kg^{-1}), K (0.09 cmolc(+) kg^{-1}), Na (0.12 cmolc(+) kg^{-1}), base saturation (235%), P retention (52.84%), Si in allophone (11.50%), active Al (0.60%), and active Fe (1.99%). Volcanic ash containing 57% SiO_2 is regarded as basaltic andesite. The mineralogy of volcanic ash is dominated by volcanic glass and labradorite.

2.2. Rice-farming systems

In the SW, rice is mostly cultivated three times a year as long as irrigation water is available in lowland areas and two times a year in highland areas shifted with vegetables. Irrigation water is usually supplied through irrigation canals and river tributaries. Nitrogen, phosphorus, and potassium are applied in the form of a single nutrient fertilizer (urea, SP-36, and KCl) or compound fertilizer with rates ranging within 46–184 kg N ha^{-1}, 36–72 kg P_2O_5 $ha^{-1,}$ and 6.3–63 kg K_2O ha^{-1} (information from surveyed farmers in study sites). However, KCl is rarely or even not applied in most sawah in the SW because farmers think KCl strengthens only the stall of rice and farmers only need the rice grains. Chemical SiO_2 fertilizer has been never applied to the soil, and SiO_2 has been supplied only from straw returned after harvesting. In terms of straw management in the SW, farmers preferred to burn the straw to shorten the time for the next planting season and thus prevent disease spread in some sites (personal comm. 2009).

2.3. Soil, plant, and water sampling

We collected 146 soil samples based on land-use types and position in the watershed. River sediments were also collected from 23 points to determine available Si. The samples were air dried, ground, and passed through a 2 mm sieve. Plant samples (rice flag leaf) were collected from several sites where soils were sampled. We collected water samples at five points along main rivers and determined the concentration of Si in water every month from August 2006 to February along the SW (Fig. 2) under collaboration with local farmers and staff of Andalas University. A total of 11 water sampling points in the SW were collected from the upper to lower streams of the rivers.

2.4. Soil chemical analyses

We collected 146 soil samples based on land-use types and position in the watershed. River sediments were also collected from 23 points to determine available Si. The samples were air dried, ground, and passed through a 2 mm sieve. Available Si was extracted using 1 mol L^{-1} acetate buffer (pH 4.0) at a mixing ratio of 1:10 for 5 h at 40 °C with occasional shaking (Imaizumi and Yoshida, 1958). Then, the concentration of Si in the filtrate was measured by molybdenum-blue method at 810 nm. TC was determined by the dry combustion method using a Yanaco CN Corder Model MT-700. Soil pH was measured using the glass-electrode method with a soil/water ratio of 1:2.5 (IITA, 1979; McLean, 1982). Exchangeable base cations (Na, Ca, and K) were extracted using 1 mol L^{-1} neutral ammonium acetate (Thomas, 1982), and exchangeable Ca was determined using inductively coupled plasma–atomic emission spectroscopy (Shimadzu ICPS2000, Kyoto, Japan). Exchangeable K and Na were determined using an atomic absorption spectrophotometer (Shimadzu AS 680). Percentage sand and clay were determined by pipette method (Gee and Bauder, 1986). Extractable Fe was extracted by 0.1 M HCl and measured with ICP (SSSA 1996). Rice plant was ground into powder, using a tungsten carbide vibrating mixer mill and digested with HNO_3 in a high-pressure Teflon vessel (Koyama & Sutoh, 1987). DSi concentration in water samples was determined with an atomic absorption spectrophotometer (Hitachi Z-5000).

2.5. Estimation of soil-erosion rate by the USLE model

Soil-erosion rate in the SW was estimated by USLE (Wischmeier and Smith, 1978). We estimated the soil-erosion rate in the SW using USLE (Aflizar and Masunaga, 2013), which expressed as:

$$E = R \times K \times L \times S \times C \times P \tag{1}$$

where P is a factor that accounts for the effects of soil-conservation practices (dimensionless), C is the crop cover factor (dimensionless), S is slope factor (dimensionless), L is length of the slope factor (dimensionless), K is the inherent soil erodibility (dimensionless), R is the rainfall erosivity factor (dimensionless), and E is the estimated soil loss (Mg $ha^{-1}y^{-1}$).

The watershed was divided by 39 312 grids with 125 m × 125 m mesh size, and basic data were allocated or estimated in each grid by reading maps and a Landsat image for land-use types and altitude or the kriging method for precipitation and soil properties. Based on these data, respective USLE factors were calculated in each grid unit. To calculate average soil erosion, we excluded the negative value of soil erosion. We used the USLE model because other models require difficult collection of data of detailed rainfall and technical constraint. Detailed calculations of each USLE factor in the SW were have been described by Aflizar et al. (2010).

2.5.1. Rainfall erosivity factor (R) and K-factor

R-factor represents the potential ability of the rain to cause soil erosion. To compute the monthly value of the R-factor (Aflizar and Masunaga, 2013):

$$R = 6.19(Rf)^{1.21}(Rn)^{-0.47}(Rm)^{0.53} \tag{2}$$

where and Rm is the maximum rainfall for a 24 h period in the observed month, Rn is number of rainy days per month, Rf is total monthly rainfall, and R is monthly erosivity. Table 1 shows the general monthly rainfall data and monthly values of the R-factor calculated with the above equation for two study periods. No clear dry season appeared in the study area, and the monthly rainfall and R-factor showed no clear seasonal pattern, highly fluctuating year by year.

The R-factor and soil erodibility (K)-factor are generally the most important factors requiring evaluation based on local conditions for the successful application of the model. Not all grids possessed their own data of precipitation or soil analyses to calculate R- and K-factors. In this case, interpolation by the nearest-neighbor kriging method (Golden software 2002) assigned the value of the nearest grid possessing soil-analysis data. This method is useful and yields good results as reported by Aflizar and Masunaga (2013) and Goovaerts (2000). The value for K-factor was computed using by Aflizar and Masunaga (2013):

$$100K = 2.713M^{1.14}(10 - -4)\ (12 - -a) + 3.25(b - 2) + 2.5(c - 3) \tag{3}$$

where M is given by [(St – Svf)/100] – Cf; a is the percentage of soil organic matter content; b is the structural code; c is the permeability class code of the soil; and St, Svf, and Cf are the percentage of silt, very fine sand, and clay fractions, respectively. Details are found in the study of Aflizar et al. (2010).

Table 1
Available SiO_2 (mg/kg) and erosion-factor analyses in sampling sites in the Sumani watershed.

Location	Sub watershed	Land use	GPS reading							Erosion Mg/ha/yr	SiO_2 (0–20) mg SiO_2/kg	SiO_2 status in soil
			East	South	R	K	LS	C	P			
Jawi-jawi 1	Sumani	Sawah	681,009	9,898,946	2452	0.1	0.064	0.01	0.4	5	204.64	d
Jawi-jawi 2	Sumani	Sawah	681,007	9,898,924	2452	0.1	0.064	0.01	0.4	5	559.71	l
Jawi-jawi 3	Sumani	Sawah	680,846	9,899,016	2452	0.1	0.064	0.01	0.4	10	138.86	d
Gantung ciri 1	Sumani	Sawah	679,766	9,900,725	2452	0.3	0.001	0.01	0.4	0.1	258.86	d
Gantung ciri 2	Sumani	Sawah	679,906	9,900,722	2452	0.3	0.001	0.01	0.4	0.1	308.79	l
Gantung ciri 3	Sumani	Sawah	679,994	9,900,676	2452	0.3	0.001	0.01	0.4	5	271.93	d
Kelok Duri	Sumani	Sawah	682,301	9,909,213	2452	0.1	0.064	0.01	0.4	2	207.86	d
Selayo	Sumani	Sawah	682,677	9,909,496	2452	0.1	0.064	0.01	0.4	2.5	127.07	d
Sawah sudut 1	Sumani	Sawah	682,689	9,909,403	2452	0.1	0.064	0.01	0.4	2	201.64	d
Sawah sudut2	Sumani	Sawah	682,753	9,909,451	2452	0.1	0.064	0.01	0.4	2	200.79	d
Gawan-sungai 1	Sumani	Sawah	682,988	9,911,695	2452	0.3	0.001	0.01	0.4	15	145.5	d
Gawan-sungai 2	Sumani	Sawah	683,204	9,911,613	2452	0.3	0.001	0.01	0.4	10	148.29	d
Gawan-sungai 3	Sumani	Sawah	683,159	9,911,560	2452	0.3	0.001	0.01	0.4	15	250.71	d
Batu Banyak 1	Lembang	Sawah	690,240	9,894,285	1665	0	0.611	0.01	0.4	5	157.07	d
Bukik Sileh 2	Lembang	Sawah	690,168	9,894,089	1665	0	0.611	0.01	0.4	5	168	d
Anau kadok 4	Lembang	Sawah	690,190	9,894,077	1665	0	0.611	0.01	0.4	5	331.07	l
Bukik Sileh 4	Lembang	Sawah	690,146	9,894,586	1665	0	0.611	0.01	0.4	7.5	230.14	d
Koto Lawas 1	Lembang	Sawah	690,485	9,898,085	2452	0	1.744	0.01	0.4	0.2	148.07	d
Koto Lawas 2	Lembang	Sawah	690,385	9,898,220	2452	0	1.744	0.01	0.4	0.2	308.14	l
Koto Lawas 3	Lembang	Sawah	690,391	9,898,224	2452	0	1.744	0.01	0.4	10	241.71	d
Batu banyak	Lembang	Sawah	689,859	9,899,180	2452	0.1	0.064	0.01	0.4	15	203.57	d
Koto Anau	Lembang	Sawah	687,948	9,902,605	2452	0.5	0.064	0.01	0.4	5	124.29	d
Sawah Durian 2	Lembang	Sawah	687,963	9,902,709	2452	0.5	0.068	0.01	0.4	5	192.64	d
Sawah Durian 3	Lembang	Sawah	688,040	9,902,988	2452	0.3	0.064	0.01	0.4	5	165.21	d
Pandan Putih 1	Aripan	Sawah	684,981	9,909,986	2452	0.3	0.064	0.01	0.4	5	339.86	l
Pandan Putih 2	Aripan	Sawah	684,868	9,910,153	2452	0.3	0.064	0.01	0.4	5	249.64	d
Rawang sari	Aripan	Sawah	684,560	9,910,295	2452	0.3	0.064	0.01	0.4	5	427.07	l
Pandan ujung 1	Aripan	Sawah	685,806	9,912,702	2452	0.1	0.001	0.01	0.4	5	89.36	d
Pandan ujung 2	Aripan	Sawah	685,820	9,912,612	2452	0.1	0.001	0.01	0.4	5	164.79	d
Pandan ujung 3	Aripan	Sawah	685,664	9,912,492	2452	0.1	0.001	0.01	0.4	5	192	d
Pandan ujung 6	Aripan	Sawah	685,437	9,912,538	2452	0.1	0.001	0.01	0.4	5	184.71	d
Parambahan 1	Aripan	Sawah	690,900	9,902,399	2452	0.3	0.611	0.01	0.4	1.8	306.43	l
Parambahan 2	Lembang	Sawah	690,786	9,902,411	2452	0.3	0.611	0.01	0.4	1.8	280.5	d
Parambahan 3	Lembang	Sawah	690,734	9,902,391	2452	0.3	0.064	0.01	0.4	0.2	227.14	d
Sungai janih	Lembang	Sawah	686,383	9,898,559	2452	0.1	0.064	0.01	0.4	15	113.36	d
Gunung Talang	Lembang	Sawah	686,155	9,898,931	2452	0.1	0.064	0.01	0.4	10	162.64	d
Batu Bajanjang	Lembang	Sawah	686,201	9,898,830	2452	0.1	0.064	0.01	0.4	10	120.86	d
Air angek 1	Lembang	Sawah	684,168	9,898,356	2452	0.3	0.064	0.01	0.4	5	500.57	l
Anau Kadok 2	Lembang	Sawah	684,089	9,898,413	2452	0.3	0.064	0.01	0.4	5	139.5	d
Anau Kadok 3	Lembang	Sawah	684,138	9,898,260	2452	0.3	0.064	0.01	0.4	10	243.21	d
Pasar usang	Lembang	Sawah	684,550	9,903,109	2452	0.3	0.064	0.01	0.4	5	374.57	l
Panyalaian Cupak	Lembang	Sawah	684,404	9,903,287	2452	0.3	0.064	0.01	0.4	0.2	364.71	l
Kubu	Gawan	Mixed Garden	679,336	9,910,716	2452	0.3	2.512	0.2	0.5	640	534.86	l
Parak gadang	Gawan	Mixed Garden	680,767	9,911,154	2452	0.3	0.064	0.2	0.5	45	445.29	l
Gunung Talang	Sumani	Mixed Garden	681,796	9,902,683	2452	0.1	0.064	0.2	0.5	30	476.79	l
Gantung Ciri	Sumani	Mixed Garden	679,878	9,903,305	2452	0.2	0.064	0.2	0.5	5	211.71	d
Curang gadang sasak	Sumani	Sawah	677,000	9,902,000	2452	0.1	2.512	0.01	0.4	115	262.29	d
Kayu aro	Sumani	Tea	680,022	9,890,308	1665	0.1	0.064	0	1	20	326.79	l
Pasar usang guguk	Lembang	Mixed Garden	682,500	9,898,000	2452	6.1	0.064	0.2	0.5	45	679.07	h
Koto baru	Lembang	Sawah	683,508	9,905,910	2452	0.2	0.064	0.01	0.4	3	508.07	h
Lembang	Aripan	Bush	681,302	9,914,208	2452	0.2	0.001	0.95	0.4	1	543	h
Jawi-jawi	Sumani	Mixed Garden	679,878	9,903,305	2452	0.2	0.064	0.2	0.5	5	955.71	h
Sukarami BPTP	Sumani	Bush	680,390	9,895,606	1665	0.1	0.064	0.29	1	15	447.86	l
Danau kambar	Sumani	Tea	680,586	9,890,624	1665	0.1	0.064	0	1	15	217.93	d
Air batumbuk	Lembang	Bush	685,164	9,886,435	1665	0.2	0.064	0.29	1	85	260.79	d
Bungo tanjung	Lembang	Mixed Garden	693,126	9,883,658	1665	0.1	1.744	0.2	0.5	5	382.71	l
Air tawar	Lembang	Mixed Garden	691,000	9,887,152	1665	0.1	2.512	0.2	0.5	30	497.79	l
Bukik sileh	Lembang	Sawah	688,906	9,894,277	1665	0	2.138	0.01	0.4	5	509.14	l
Koto anau	Lembang	Sawah	687,977	9,902,100	2452	0.2	0.001	0.01	0.4	5	245.79	d
Air Mati	Aripan	Bush	684,848	9,912,166	2452	0.3	2.138	0.95	0.4	1	616.29	h
Bukik gompong	Sumani	Mixed Garden	681,722	9,895,558	1665	0.1	2.138	0.2	0.5	85	576.64	l
Kampung jawa 1	Sumani	Mixed Garden	682,165	9,894,832	1665	0.1	2.138	0.2	0.5	65	857.14	h

(*continued on next page*)

Table 1 (*continued*)

Location	Sub watershed	Land use	GPS reading East	GPS reading South	R	K	LS	C	P	Erosion Mg/ha/yr	SiO_2 (0–20) mg SiO_2/kg	SiO_2 status in soil
Kampung jawa 2	Sumani	Mixed Garden	682,148	9,894,165	1665	0	3.613	0.2	0.5	10	227.36	d
Tower TVRI 2	Sumani	Forest	682,440	9,893,752	1665	0	2.877	0	1	40	316.5	l
Tower bukik gompong	Sumani	Forest	683,120	9,893,547	1665	0.1	2.877	0	1	5	358.29	l
Laing 1	Aripan	Grass	680,718	9,915,222	2452	0.1	0.001	0.29	1	2.5	89.36	d
Laing 2	Aripan	Forest	685,090	9,917,469	2452	0.5	2.138	0	1	3.5	560.79	l
Laing 3	Aripan	Grass	685,251	9,917,230	2452	0.5	2.138	0.29	1	285	243.86	d
Laing 4	Aripan	Mixed Garden	685,283	9,917,147	2452	0.5	2.138	0.2	0.5	270	98.57	d
Saok laweh	Aripan	Sawah	686,353	9,912,829	2452	0.1	0.001	0.01	0.4	5	261	d
Ganangan	Lembang	Mixed Garden	684,733	9,906,341	2452	0.2	0.064	0.2	0.5	10	437.36	l
Balai pinang	Lembang	Sawah	685,276	9,905,296	2452	0.3	0.064	0.01	0.4	0.2	289.29	d
Guguk rantau	Lembang	Bush	682,703	9,906,436	2452	0.2	0.064	0.29	1	5	372	l
Koto baru	Lembang	Forest	682,595	9,906,283	2452	0.2	0.001	0	1	5	791.14	h
Sawah suduk	Sumani	Bush	682,276	9,908,944	2452	0.1	0.064	0.29	1	5	313.29	l
Pakan senayan	Sumani	Mixed Garden	680,780	9,906,663	2452	0.1	0.064	0.2	0.5	1.6	201.21	d
Selayo	Gawan	Sawah	679,843	9,907,068	2452	0.3	0.064	0.01	0.4	5	264.43	d
Durian X koto	Gawan	Forest	680,026	9,914,546	2452	0.1	0.001	0	1	0	153.64	d
Koto sani	Imang	Bush	678,451	9,916,455	2452	0.3	0.001	0.29	1	0.2	309	l
Aie angek	Imang	Mixed Garden	678,169	9,915,663	2452	0.2	2.512	0.2	0.5	123.2	355.71	l
Sumani 1	Imang	Sawah	677,426	9,921,191	1288	0.1	0.001	0.01	0.4	5	292.5	d
Panyalaian Cupak	Lembang	Sawah	684,275	9,903,267	2452	0.3	0.064	0.01	0.4	5	299.36	d
Sumani 2	Aripan	Sawah	677,681	9,921,448	1288	0.1	0.001	0.01	0.4	5	128.36	d
Aur Duri	Imang	Sawah	678,648	9,919,152	1288	0.1	0.064	0.01	0.4	25	392.14	l
Belimbing	Imang	Sawah	678,905	9,916,775	2452	0.3	0.001	0.01	0.4	3	313.5	l
Durian	Aripan	Sawah	680,453	9,914,773	2452	0.1	0.001	0.01	0.4	4	295.93	d
Sawah Parit	Aripan	Sawah	685,480	9,910,916	2452	0.3	0.064	0.01	0.4	10	182.36	d
Guguk Dama	Aripan	Sawah	685,080	9,909,609	2452	0.3	0.064	0.01	0.4	5	228.64	d
Batu Juriang	Aripan	Sawah	686,098	9,908,995	2452	0.2	0.064	0.01	0.4	10	288.86	d
Muaro Paneh	Aripan	Sawah	687,639	9,906,755	2452	0.2	0.064	0.01	0.4	4	120.64	d
Koto Gadang Koto Anau	Lembang	Sawah	687,895	9,903,389	2452	0.3	0.064	0.01	0.4	5	200.57	d
Koto Anau	Lembang	Sawah	688,034	9,902,271	2452	0.2	0.064	0.01	0.4	5	235.93	d
Koto Laweh	Lembang	Sawah	690,464	9,898,410	1665	0	1.744	0.01	0.4	3	200.79	d
Bukit Sileh	Lembang	Sawah	691,249	9,895,502	1665	0.1	0.064	0.01	0.4	20	196.7	d
Bukit Sileh 2	Lembang	Vegetable	691,275	9,895,481	1665	0.1	0.064	0.4	0.5	20	203.79	d
Kampung Batu	Lembang	Sawah	691,024	9,893,027	1665	0.1	0.064	0.01	0.4	5	310.29	l
Kampung Batu 2	Lembang	Vegetable	691,156	9,891,364	1665	0.1	0.064	0.4	0.5	50	102.43	d
Dilam 1	Lembang	Sawah	692,432	9,900,886	1665	0.3	3.399	0.01	0.4	10	157.5	d
Dilam 2	Lembang	Sawah	692,462	9,900,828	1665	0.3	3.399	0.01	0.4	10	152.79	d
Dilam 3	Lembang	Sawah	692,483	9,900,815	1665	0.3	3.399	0.01	0.4	10	189.43	d
Sumani 3	Aripan	Mixed Garden	677,030	9,921,312	1288	0.1	0.001	0.01	0.4	0	412.07	l
Aripan 1	Aripan	Mixed Garden	676,813	9,922,182	1288	0.1	0.001	0.2	0.5	0	355.29	l
Aripan 2	Aripan	Mixed Garden	678,613	9,919,968	1288	0.1	0.064	0.2	0.5	1	1115.36	h
Aripan Pompa	Aripan	Mixed Garden	679,004	9,919,123	1288	0.1	0.064	0.2	0.5	1	756.43	h
Tanjung Bingkung	Aripan	Mixed Garden	680,785	9,916,791	2452	0.3	0.611	0.2	0.5	56	427.93	l
Bbanda pandan	Aripan	Mixed Garden	681,581	9,913,781	2452	0.2	0.001	0.2	0.5	1	633	h
Kota Solok	Aripan	Mixed Garden	684,026	9,911,713	2452	0.3	0.064	0.01	0.4	1	634.5	h
Batu kualo	Lembang	Mixed Garden	684,727	9,909,217	2452	0.2	0.064	0.2	0.5	5	296.36	d
Muaro paneh	Lembang	Mixed Garden	686,990	9,906,478	2452	0.2	0.064	0.2	0.5	5	200.79	d
Lembang atas	Lembang	Mixed Garden	688,122	9,900,659	2452	0.1	0.611	0.2	0.5	28	391.5	l
Bukik sileh	Lembang	Mixed Garden	690,986	9,894,498	1665	0.2	3.4	0.2	0.5	200	389.79	l
Batu banyak	Lembang	Mixed Garden	691,380	9,891,131	1665	0.1	0.611	0.2	0.5	14	794.14	h
Kubung	Lembang	Mixed Garden	684,313	9,907,711	2452	0.2	0.064	0.2	0.5	5	166.93	d
Bukik kili 1	Lembang	Mixed Garden	684,276	9,906,492	2452	0.2	0.064	0.2	0.5	5	375	l
Bukik Kili 2	Lembang		683,659	9,905,507	2452	0.3	0.064	0.2	0.5	0	329.14	l

(*continued on next page*)

Table 1 (*continued*)

Location	Sub watershed	Land use	GPS reading							Erosion Mg/ha/yr	SiO_2 (0–20) mg SiO_2/kg	SiO_2 status in soil
			East	South	R	K	LS	C	P			
		Mixed Garden										
Cupak sungai	Lembang	Mixed Garden	683,030	9,903,030	2452	0.3	0.064	0.2	0.5	5	308.57	l
Talang	Lembang	Mixed Garden	683,500	9,900,067	2452	0.2	0.064	0.2	0.5	5	334.71	l
Lubuk silasih	Sumani	Mixed Garden	677,332	9,893,200	1665	0.1	1.74	0.2	0.5	56	216.21	d
Lubuk silasih 2	Sumani	Mixed Garden	677,090	9,893,546	1665	0.1	0.61	0.2	0.5	5	391.07	l
Lubuk selasih 3	Sumani	Forest	675,194	9,893,700	1665	0.1	0.001	0.2	0.5	1	106.29	d
Kapalo banda	Sumani	Mixed Garden	680,662	9,901,560	2452	0.3	0.001	0.01	0.4	0	289.29	d
Kota Solok 2	Lembang	Mixed Garden	683,872	9,910,003	2452	0.3	0.064	0.2	0.5	5	229.07	d
Kota Solok 3	Lembang	Mixed Garden	683,981	9,909,967	2452	0.3	0.001	0.2	0.5	1	343.29	l
Aripan 3	Aripan	Mixed Garden	681,485	9,920,988	1288	0.1	0.001	0.2	0.5	1	101.57	d
Kubung 1	*Sumani*	*Sawah*	*683,541*	*9,910,512*	2452	0.3	0.001	0.01	0.4	1	209.57	d
Kubung 2	*Sumani*	*Sawah*	*682,817*	*9,910,806*	2452	0.3	0.064	0.01	0.4	1	179.14	d
Batu palano	Gawan	sawah	680,861	9,911,165	2452	0.3	0.064	0.2	0.5	5	220.07	d
Ketaping 1	Gawan	Sawah	680,081	9,910,640	2452	0.3	0.611	0.01	0.4	1	201.86	d
Ketaping 2	Gawan	Mixed Garden	679,815	9,910,540	2452	0.3	0.611	0.2	0.5	100	282.86	d
Ketaping 3	Gawan	Sawah	679,659	9,910,488	2452	0.3	0.611	0.01	0.4	1	220.07	d
Ketaping 4	Gawan	Mixed Garden	679,437	9,910,599	2452	0.3	0.064	0.2	0.5	5	137.57	d
Gawan 1	Gawan	Forest	679,098	9,910,622	2452	0.3	2.51	0	1	1	136.29	d
Bukit kili 1	Gawan	Forest	678,850	9,910,573	2452	0.1	2.51	0	1	1	130.29	d
Bukit Kili 2	Gawan	Sawah	682,115	9,911,144	2452	0.3	0.064	0.01	0.4	1	255.86	d
Aripan 4	*Aripan*	*Sawah*	*682,803*	*9,913,171*	2452	0.2	0.001	0.01	0.4	5	127.29	d
Aripan 5	*Aripan*	Mixed Garden	*682,701*	*9,914,550*	2452	0.2	0.001	0.2	0.5	0	150.21	d
Destamar 1	*Aripan*	Mixed Garden	*682,863*	*9,916,064*	2452	0.1	0.001	0.2	0.5	0	94.07	d
Destamar 2	*Aripan*	Mixed Garden	682,652	9,917,803	2452	0.4	0.064	0.2	0.5	100	113.36	d
Destamar 3	*Aripan*	Mixed Garden	682,652	9,917,803	2452	0.4	2.14	0.2	0.5	100	263.57	d
Gantung Ciri 1	Sumani	Sawah	680,501	9,903,987	2452	0.1	0.064	0.01	0.4	1	309.86	l
Gantng Ciri 2	Sumani	*Sawah*	*679,916*	*9,904,572*	2452	0.2	0.001	0.01	0.4	1	292	d
Puluan 1	Sumani	Mixed Garden	679,772	9,904,605	2452	0.2	0.064	0.2	0.5	1	421.93	l
Puluan 2	Sumani	Sawah	679,503	9,904,591	2452	0.2	0.064	0.01	0.4	1	313.5	l
Puluan 3	Sumani	Mixed Garden	*679,278*	*9,904,592*	2452	0.2	0.611	0.2	0.4	14	194.36	d
Bukik Singo-singo	Sumani	Mixed Garden	679,032	9,904,638	2452	0.2	0.611	0.4	0.5	56	178.71	d
Bukik Singo-singo 2	Sumani	Mixed Garden	*680,264*	*9,904,469*	2452	0.2	0.611	0.01	0.4	28	274.07	d
				Mean							299.8	
				Median							259.83	
				Max							1115.36	
				Min							89.36	
				SD							177.21	

Where, d is deficiency concentration of Si; l is low concentration of Si; h is high concentration of Si.

2.5.1.1. Slope length and steepness factor (LS). Each grid was considered as a single slope plane. The LS factor was calculated using a so-called power form of equation (Wischmeier and Smith 1978). Aflizar et al. (2010) reported that the exponent of slope length in the equation did not change with an increase in the slope gradient from 20% to 60%; however, it changed when the slope gradient was less than 20%. Therefore, in the present study, two equations, i.e. (4) for slope gradient less than 20% and (5) for slope gradient > 20%, were separately used.

$$LS = (L/22)^{m}(65.41\ \sin 2X - -4.56\ \sin X + 0.065) \quad (4)$$

$$LS = (L/22)^{0.7}(6.432\ \sin (0.79X)\ \cos (X)) \quad (5)$$

where L is the slope length in m, S is the slope percentage, X is the slope in degrees, and m is the exponent that varies with slope gradients as in 0.2 for < 1%, 0.3 for 1%–3%, 0.4 for 3.5%–4.5% and 0.5 for > 5% (Table 1).

2.5.1.2. Cover crop (C) and conservation practice (P) factors. Land-use types in the SW were investigated by interpreting image photos of Landsat TM 2002 confirmed with a field survey in August 2007 and land-use map 1992 based on air photos to have C- and P-factors (Table 1). Different land-use types had respective C-factors. Forest had the smallest and vegetable gardens had the highest C-factor, except for settlement. Major soil conservation practices used in the SW were ground coverage by grass or shrub in vegetable, mixed and coconut gardens, and terrace in Sawah.

2.6. Data processing for 3D mapping

Overall data processing involving USLE was conducted using Surfer® 8 (Golden software 2010) dealing with factors gained from a detailed soil survey, digital elevation model, and land-use map. The map of available Si, soil erosion, and land use were computed subsequently using block kriging by taking account of the data within the range. Block kriging was used instead of punctual kriging because it enables the evaluation of the regional pattern of variation rather than local details owing to the construction of smoother maps with smaller estimation variance (Aflizar et al., 2010). Surfer® 8, produced by Golden Software, Inc. (Golden Colorado), is a relatively inexpensive and user-friendly countering and three-dimensional surface mapping software for scientists and engineers. Basic proficiency with Surfer® 8 can be achieved with a few hours of self-tutoring. Various editions of Surfer® 8 have been applied to the modelling and evaluation of soil heavy-metal contamination and other environmental data (Pazmandi and Tuba 2003). Reported applications typically use Surfer tool as an interface with other software rather than as a stand-alone analytical tool (Aflizar et al., 2010). Surfer software is extensively used but not well documented, with only limited reference to its application to environmental data existing in scientific literature.

In this study, we used universal kriging that assumed a constant and unknown mean. As shown in Fig. 1, samples were collected throughout the study area, with the exception of the area at the very steep slope and common land-use forest at the west side of SW because of lack of access to the area. Thus, a polygon with boundaries limiting the area of sampling was used, and estimates were generated only for the area inside it. We used cross-validation to estimate the kriging density through different approaches.

3. Result

3.1. General soil physicochemical properties

Tables 1 and 2 show general soil physicochemical properties in the SW. The soil had high silt and clay contents (values of silt and clay contents) and organic matter content of about 5%, which high value (Balai Penelitian Tanah, 2009). Soil permeability and erodibility were high. According to Wischmeier and Smith (1978), soils with K-factor > 0.04 are generally susceptible to soil erosion. Soil susceptibility to erosion is highly influenced by different climatic, physical, hydrological, chemical, mineralogical, and biological properties (Veihe, 2002). Total nitrogen and available Si are low, whereas TC, extractable Fe and Zn are high. Exchangeable base cations (Ca, Mg, K, and Na) were relatively high. Soil physicochemical properties had some correlation with available Si in the SW (Table 2). Table 2 reveals that the physical properties of the soil in the form of 32% clay content and 55% silt are quite high as an indicator of good soil physical condition for sawah. Medium to high levels of TC, TN, Ca, K and Na as macronutrients for sawah are good for supporting sustainable management of sawah. However, after analysing available Si in the soil in SW, the concentration of Si was 80% (<300 mg SiO_2 kg^{-1}), indicating deficiency.

Table 2
General soil physicochemical properties in the Sumani watershed.

	Mean	Criteria	(Range)	SD	r[a]
Sand (%)	9.0		(0.4–58.0)	11	0.08
Very fine sand (%)	2.0		(0.4–9.0)	2	0.01
Silt (%)	55.0		(0.0–85.0)	20	0.02
Clay (%)	33.0		(9.0–95.0)	20	−0.05
Organic matter (g kg^{-1})	54.0	h	(21.0–111.0)	24	0.01
Soil permeability (cm h^{-1})	93.0		(0.0–1506.0)	286	0.01
Soil erodibility (K)	0.22	h	(0.0–0.5)	0.1	0.17*
Bulk density (g cm^{-3})	0.9		(0.5–1.3)	0.2	0.01
Soil pH H2O 1:2.5	5.5	a	(4.2–7.2)	0.5	0.32**
Total Carbon (g kg^{-1})	34.6	h	(7.2–151.4)	27.6	0.01
Total Nitrogen (g kg^{-1})	3	m	(0.4–9)	0.17	0.01
Exchangeable Ca (cmolc (+) kg^{-1})	10.6	m	(0.023–29.7)	6.1	0.45**
Exchangeable K (cmolc (+) kg^{-1})	0.4	m	(0.1–1.9)	0.4	0.38**
Exchangeable Na (cmolc (+) kg^{-1})	0.9	h	(0.002–3.7)	0.7	−0.28**
Extractable Fe (mg kg^{-1})	204.2	h	(0.02–1500.6)	289	−0.17*
Available Si 0–20 cm (mg SiO2 kg^{-1})	300.0	l	(89.4–1115.4)	177	

**, P Value < 0.01 and *, P value < 0,05; SD is standar deviation; r is correlation; h is high; m is medium; l is low; a is acid.

This occurred because since the introduction of the Green Revolution in Indonesia in 1974, the Indonesian government only recommended the use of N, phosphate and K fertilisers; pesticides; and irrigation in sawah. This practice is still being continued to date (Aflizar et al., 2018). Hence, with our current findings, the sawah in the SW and Indonesia requires Si (silicate) fertilisation because the Si levels are already deficient to low. In accordance with the minimum law, Liebig states that growth is not controlled by the total available resources but is controlled by the fewest resources or nutrients (limiting factors) (Warsi and Dykhuizen, 2017). In the SW, the current growth and production of paddy sawah is determined by available Si in the soil at the deficiency level (Table 1). Unfortunately, the Indonesian government has not recommended the use of Si fertiliser, only N, P and K (Aflizar et al., 2019).

3.2. Available Si and other general soil properties

Table 3 shows the average Si concentrations available in sawah soil (262.4 mg SiO_2 kg^{-1} in deficiency levels). For sawah to produce well, available Si in the soil must be > 600 mg SiO_2 kg^{-1}. Then, where did the supply of 337.6 mg SiO_2 kg^{-1} come from so that sawah in the SW could still produce 5 tons ha^{-1}. Tables 2–4 and Fig. 4 reveal that the contributor of available Si to rice fields is from Si from the soil depth of 0–20 cm (262.4 mg SiO_2 kg^{-1}), river water and irrigation (34.7 mg SiO_2 kg^{-1}) and river sediments from erosion products (393.7 mg SiO_2 kg^{-1}).

To obtain a high production of Sawah (>5 tons ha^{-1} to 9 tons ha^{-1}), the paddy soil must have an Si content of 600 mg SiO_2 kg^{-1}, equivalent to an Si content in 1 ha = 600 mg SiO_2 kg^{-1} × 2 × 106 kg ha^{-1} × 0.9 g cm^{-3} = 1080 kg SiO_2 ha^{-1}. Thus, the lack of Si in sawah in 1 ha is = 1080 kg SiO_2 ha^{-1} − 437.5 kg SiO_2 ha^{-1} − 5.52 kg SiO_2 ha^{-1} − 472.32 kg SiO_2 ha^{-1} = 164.66 kg SiO_2 ha^{-1}. Therefore, the figure of 165 kg SiO_2 ha^{-1} is a recommendation for Si fertiliser that must be added to the sawah, so that its production increases due to the achievement of Si concentration available in 600 kg SiO_2 ha^{-1} in sawah soil. The main source of Si in this paddy soil can be taken from coal fly ash and organic matter (Darmawan et al., 2006) or from Si fertiliser directly.

Table 4 shows the average Si available in soil at 0–20 cm depth in the SW and 5 subwatershed (S1, S2, S3, S4, and S5). The Si concentration was lower than that in the Citarum watershed, Kaligarang Watershed on Java Island, and Seedfarm and Non-Seedfarm sawah on Java Island (Darmawan et al., 2006; Husnain et al., 2008). This finding may be due to the different numbers of growing seasons of sawah and the soil geology. The intensive rice cultivation has led to Si mining and exportation through harvesting processes (Darmawan et al., 2006). Differences in the parent material also appeared to be the major factor influencing Si in soils at the watershed scale (Darmawan et al., 2006; Husnain et al., 2008).

3.3. Relationships between soil chemical properties and availability of SiO_2 in the SW

pH showed a positive relationship with the availability of Si, i.e., Si availability increased with increased pH. This phenomenon may be due to the high availability of Si in high-pH soil possibly because of the

Table 3
Mean of available Si and other general soil properties in the SW.

Sampling point	pH	TC	Availa-ble Si	Exchang-eable Ca	Exchange-able Na	Exchang-eable K	Extracta-ble Fe
		(g kg^{-1})	(mg SiO2 kg^{-1})	(cmolc kg^{-1})			(mg kg^{-1})
Sawah (n = 78)	5.5	34.6	262.4	9.88	1.14	0.26	298
Mixed garden (n = 48)	5.6	45.2	375.9	13.89	0.31	0.72	114
Vegetables (n = 2)	4.6	26.7	153.1	7.32	0.29	1.28	104
Tea (n = 2)	5.3	123.9	272.4	6.07	0.25	0.22	16.3
Forest (n = 8)	5.8	57.3	319.5	13.24	0.38	0.31	19.2
Bush (n = 7)	5.6	38.2	290.9	10.57	0.40	0.30	18.7
River Sediment (n = 23)	5.5	34.6	393.7	9.88	1.14	0.26	298
			262.4				
Criteria of available Si level in sawah soil							
Deficiency level (Matichenkov, 2002)				300.0			
Low level (Sumida, 1992)				600.0			

Table 4
Average available Si in 0–20 cm soil depth of some selected sawah in the SW and other watersheds in Indonesia.

Study (reference)	Location	Area (km^2)	n soil sample	Available Si in soil (0–20 cm) depth (mg SiO_2 kg^{-1})
Sumani subwatershed (S1)	Sumatera Island	176.70	19	241.63
Lembang subwatershed (S2)	Sumatera Island	191.80	34	261.01
Gawan subwatershed (S3)	Sumatera Island	80.40	6	219.32
Aripan subwatershed (S4)	Sumatera Island	70.40	16	210.57
Imang subwatershed (S5)	Sumatera Island	64.00	3	332.71
Sumani Watershed (SW)	Sumatera Island	583.3	78	253.05
Citarum Watershed (Husnain et al., 2008)	Java Island	6949	6	504.83
Kaligarang Watershed (Husnain et al., 2008)	Java Island	210	6	460.33
Sededfarm (Darmawan et al., 2006)	Java Island		18	1283.00
Non-Sededfarm (Darmawan et al., 2006)	Java Island		22	1202.00
Sededfarm lowland (Darmawan et al., 2006)	Java Island		12	1804.00
Sededfarm upland (Darmawan et al., 2006)	Java Island		6	1005.00
Non-Sededfarm lowland (Darmawan et al., 2006)	Java Island		13	1187.00
Non-Sededfarm upland (Darmawan et al., 2006)	Java Island		6	1226.00

influence of volcanic ash from Mount Talang. According to Fiantis et al. (2010), Mount Talang volcanic ash contains CaO (4.79%), exchangeable Ca (cmol 11:14 (+) kg^{-1}), and pH H_2O 1:5 (7:26).

Volcanic ash very rapidly decays and releases nutrients compared with primary minerals. The weathering process of volcanic ash releases Ca and other elements, including available Si and K as indicated by an increase in pH (Fig. 3). Ca, K, and Si from volcanic ash are released into the soil, where the nutrients become available to the plants through the process of exchange with free hydrogen protons in the soil.

3.4. Soil-erosion map and distribution of Si availability

The soil-erosion map in the SW in 3D is presented in Fig. 4. The average rate of erosion in the SW was 58.91 Mg ha^{-1}y^{-1}. However, soil erosion was much greater than the average erosion in the highlands where the lands sloped. In the hilly area adjacent to Mount Talang (highland areas S1 and S2), soil erosion ranged within 100–200 Mg ha^{-1}y^{-1}. Meanwhile, in the hilly area that lies on the west side (upper position of S2, S3 and S5), soil erosion exceeded 200 Mg ha^{-1}y^{-1}. Conversely, in the lowlands (particularly S1, S2, S3, S4, and S5) soil erosion was very low. According to Aflizar et al. (2010), the highest soil erosion occurs in hilly areas in the SW highlands caused by land-use change from forest to agriculture and by natural factors such as erodibility added soil and high rainfall. Meanwhile, soil erosion in the lowlands was low because a sawah generally had a band to prevent erosion. The average annual erosion in the SW is 58.91 Mg ha^{-1}y^{-1}, which has produced as much sediment in the SW is 6.18 Mg ha^{-1}y^{-1}with an average of SDR is 10.5%. This finding indicated the accumulation of eroded soil particles in the flat bottom of the watershed area where the land is sawah.

Fig. 5 shows the 3D distribution of Si availability in the SW. In the highlands S1 and S2 (located near Mount Talang), Si availability was relatively higher than those in the western side of the SW, which includes the areas on the upper positions (S1, S3, and S5). We compared Fig. 3 with 4 and found high soil erosion on both sides. However, in the hilly area near the Mount Talang (the highlands Si and S2), Si availability was relatively higher those in the west areas. This finding may be due to the fact that the area around Mount Talang received fresh volcanic ash from its eruption, and the surrounding soil type is andisol derived from basalt andesite. Fiantis et al. (2010) reported that the eruption of Mount Talang on April 12, 2005 belched 5 cm-thick volcanic ash into the air before falling over the surrounding areas. Volcanic ash contains approximately 57.61% SiO_2, and the main mineral is volcanic glass and labradorite. Qafoku et al. (2004) reported that volcanic glass is more brittle and elements are more easily released to the soil solution compared with primary minerals.

Fig. 6 shows the vertical distribution of Si availability in the highlands and lowlands. We found lower availability of Si on the soil surface than in the subsoil because more Si was consumed by plants or leached into the subsoil. This result also indicated the influence of soil erosion on the distribution of Si. To examine the effect between the Si consumption by plants or Si loss by soil erosion, we attempted a simple calculation and found that the total annual production of vegetable crops, mixed gardens, and rice in the SW was 27 Gg y^{-1}, whereas the total erosion and total river sediment each year were 3436 Ggy^{-1} and 360 Ggy^{-1}, respectively. The average Si in rice leaves in java was 120350 mg SiO_2kg^{-1} (Husnain et al., 2008), and Si in the soil in the SW was 300 mg SiO2kg^{-1}. Thus, the SiO_2 lost each year through plant consumption was 3252 Mg y^{-1}, whereas the SiO_2 lost through soil erosion was 1031 Mg y^{-1}. Thus, these data illustrated that erosion greatly influenced soil Si

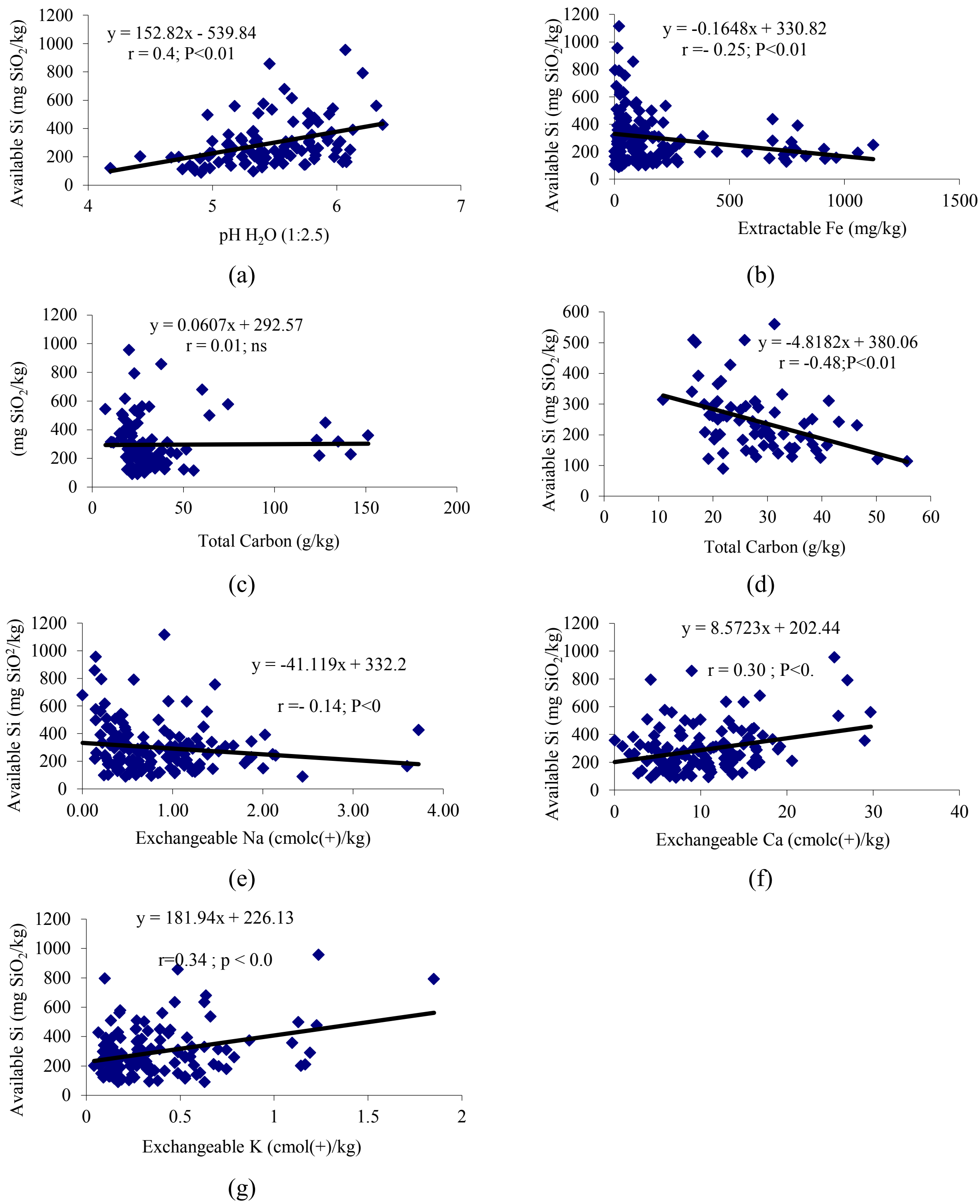

Fig. 3. Relationship between available Si and soil chemical properties of soils; (a) pH, (b) Fe, (c) total carbon in the SW, (d) total carbon in sawah, (e) Na, (f) Ca, and (g) K.

loss, and we expected to lose ground in SiO_2 from the watershed scale. We expect that the transfer layer of topsoil is eroded by erosion. Consistent with the increased erosion every year owing to changes in land use (Aflizar et al., 2010), the loss of SiO_2 in the watershed scale continued to increase every year.

Fig. 7 explains the direction of material movement due to soil erosion in the watershed, where the direction of movement Sumani material is indicated by blue arrows. The arrow was made based on altitude and slope degree in the SW simulation by using a vector in Surfer ® 9. The material apparently moved from highlands S1 and S2 and then accumulated sediment in the lowland S2. Material from the upper position while S2, S3. S4 and S5 collected in lowland S3, S4, and S5. Benefits received by the lowland area is the discovery of the availability of high Si at lower positions. This fact, probably due to the transport surface soils containing high SiO_2 through soil erosion. We also suspected that erosion increased the content of Si in river water and irrigation because the soil contained particles in the form of sediment. We subsequently observed SiO_2 in river and irrigation water.

3.5. Concentration of DSi in river water and irrigation

Dissolved Si in river and irrigation water in the Sumani watershed as shown in Fig. 8. DSi in rivers and irrigation water on average ranged from 5 to 54 mg kg^{-1} SiO_2 in the interval of observation from August

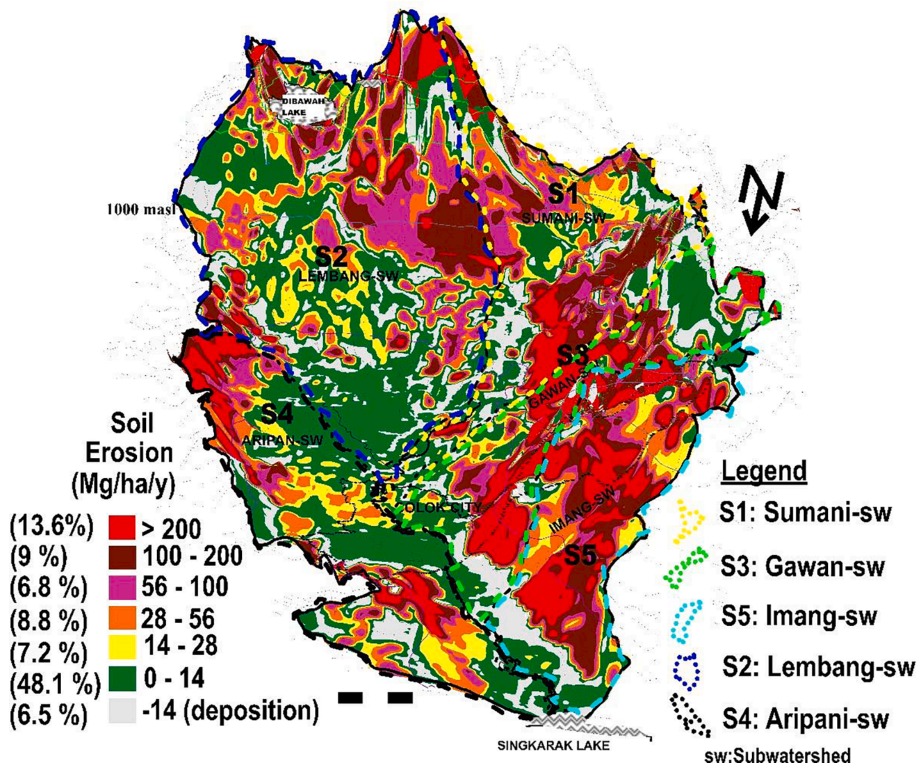

Fig. 4. 3D soil-erosion map in the SW.

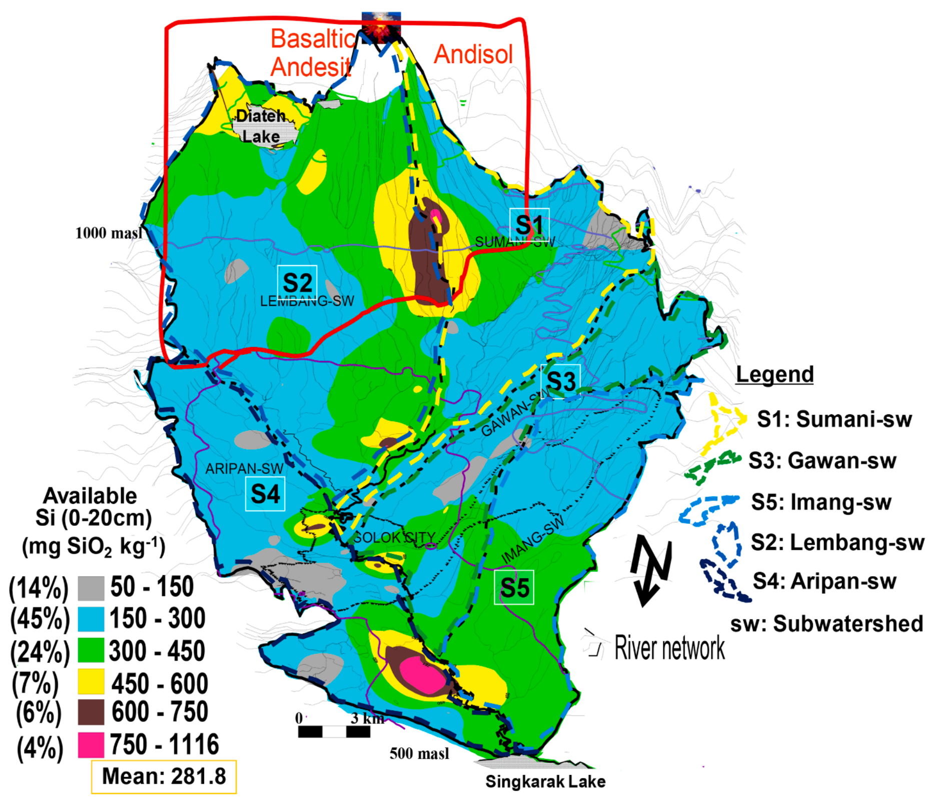

Fig. 5. Distribution of available Si in soil.

2006 until February 2007. DSi was higher in the lowlands than in the SW highlands. In the SW, DSi concentrations in water were higher than those in the DSi in the Citarum watershed, Indonesia (12.6–36.6 mg SiO_2 kg^{-1}) (Husnain et al., 2006). DSi in the second watershed was generally low because no SiO_2 fertilizer was present in the SW. Thus, DSi from rivers and irrigation water can be a source of SiO_2 fertilizer. As reported

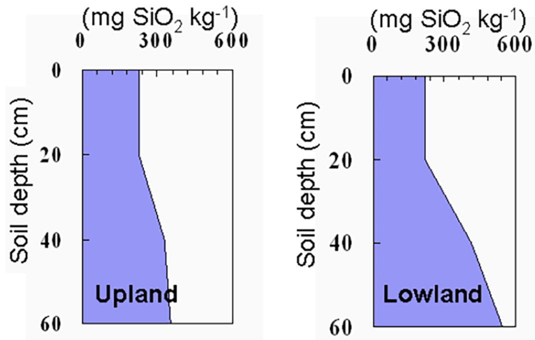

Fig. 6. Vertical distribution of available Si.

by Imaizumi and Yoshida (1958), the 30% SiO_2 sources for rice is derived from river water and irrigation water. Fiantis et al. (2010) performed laboratory experiments and found that phosphorus and other elements including Si in volcanic ash of Mount Talang are leached out within 3000 days through water as leaching agent and within<2000 days by using organic acids (citrate and oxalic acid). In summary, available-Si distribution was influenced by various factors, as shown in Fig. 9.

Table 5 shows that the average Si concentration in the river at SW was greater than those in the rivers in the Citarum and Kaligarang watersheds, as well as other Asian countries (Thailand, Malaysia, Sri Lanka, and Japan). The average Si in irrigation water in the SW was also greater than that in Java Island and irrigation water in Japan. This finding may be due to the fact that SW has a natural Si source in the highlands of Mount Talang, which greatly contributes Si to springs and rivers and irrigation. High Si concentrations in river water and irrigation in the SW are the largest contributors of Si to sawah as a counterweight to Si in the soil. The contribution of natural SiO_2 resources as irrigation water reportedly play important roles in maintaining the available-Si concentration in soil (Darmawan et al., 2006). Kawaguchi and Kawaguchi and Kyuma (1977) found moderate Si concentration in river water, which are the dominant sources of irrigation in Java Island, Indonesia.

3.6. Cross-validation of field measurements

Before using a simulation map and optimizing a mathematical model, the accuracy of the simulation map or the model with the original data should be verified (Theodossiou et al. 2006). The verification is not intended to prove the model accuracy but to ensure the absence of systematic errors, which play important roles in bias estimation (Kitanidis, 1983). The verification procedures were implemented as follows. The concentration of available Si from 146 soil-sample points were analysed in the laboratory through the same methods and equipment. With the help of kriging method in Surfer ® 8, the estimated distribution map of available Si was created. Then matched back with the result of analysis of available Si in the laboratory. The differences between the results of analyses available Si in the laboratory and the estimated values were recorded. The distribution map is considered unbiased in the sense that if the basic assumptions made were true, then the difference between the analyses of available Si map would be zero. In any other case, the estimated value would be conditionally biased. An example of this is found in the greater estimation value or smaller value measured in laboratory. Fig. 10 shows the correlation of the concentration of available Si measured with the estimation map of available Si.

The result can easily be observed that the available Si was distributed around a straight line at 45°. This finding showed that the estimation map of available Si was unbiased. The isolated points were located below 45°, indicating that the estimated value was incorrect or soil samples in locations required more soil samples. This fact explains the observation on that area needs to be a lot of soil sample, especially in the area have different in geology, land use and topography. Theodossiou and Latinopoulos (2007) reported when using kriging, the occurrence of a large difference between the laboratory and estimated values should not depend on the actual value but only on the location of soil sample, which was representative area that can be simulated (or not) by measuring the actual value. Fig. 11 shows the distribution diagram of the correlation between the estimation error (the difference between

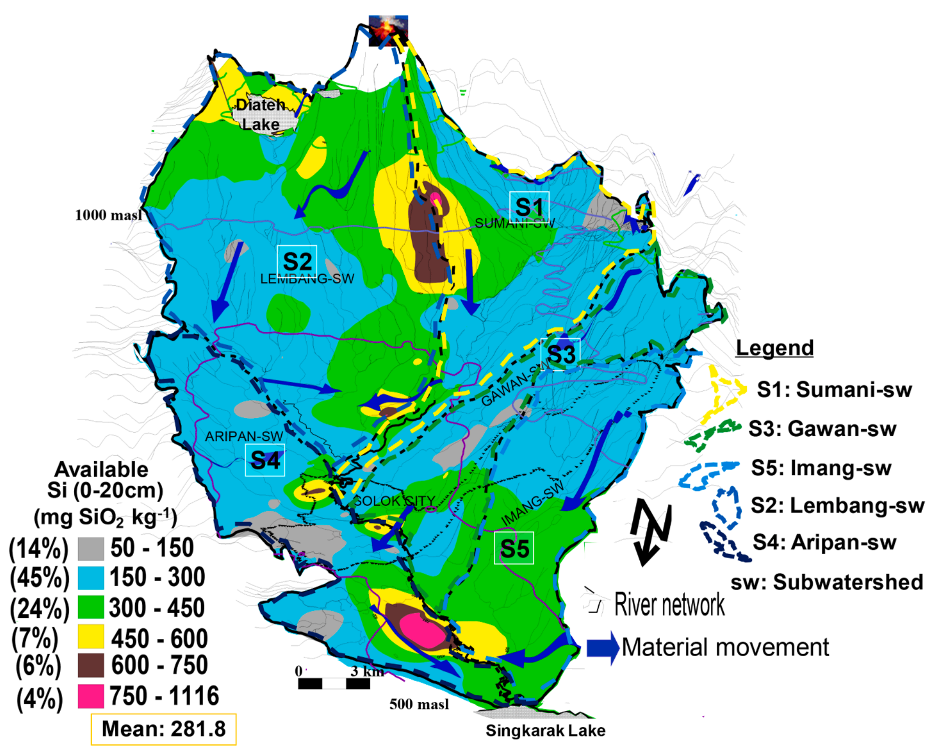

Fig. 7. Direction of material movement in the SW.

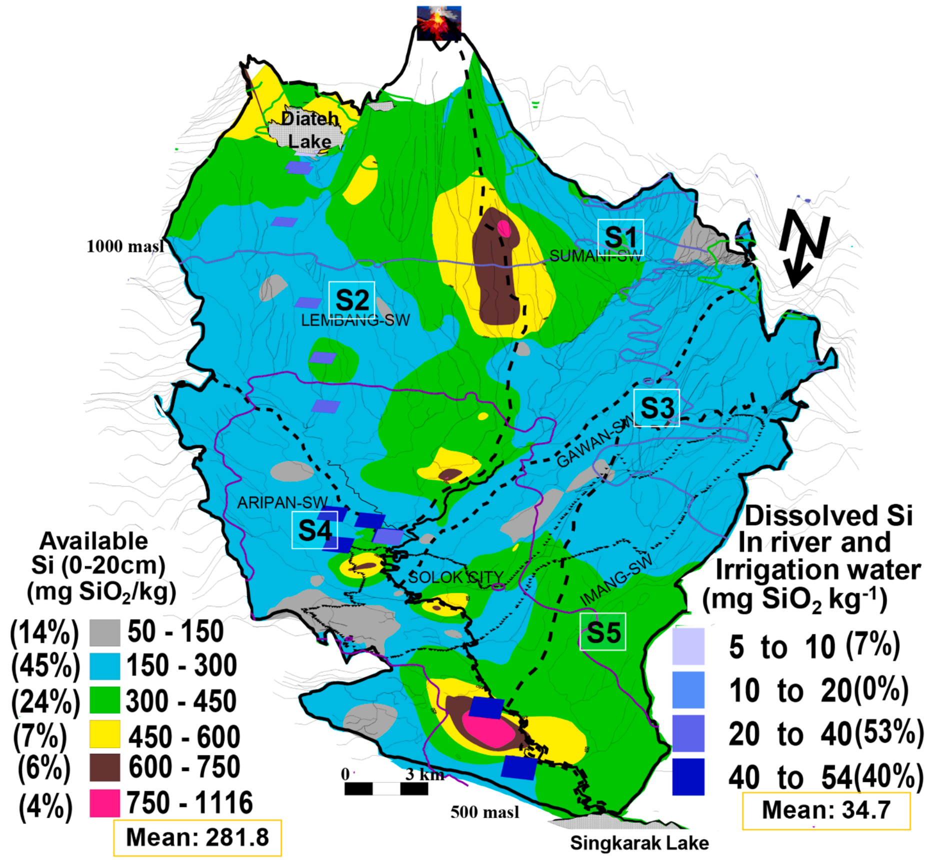

Fig. 8. Dissolved Si in river and irrigation water in the SW.

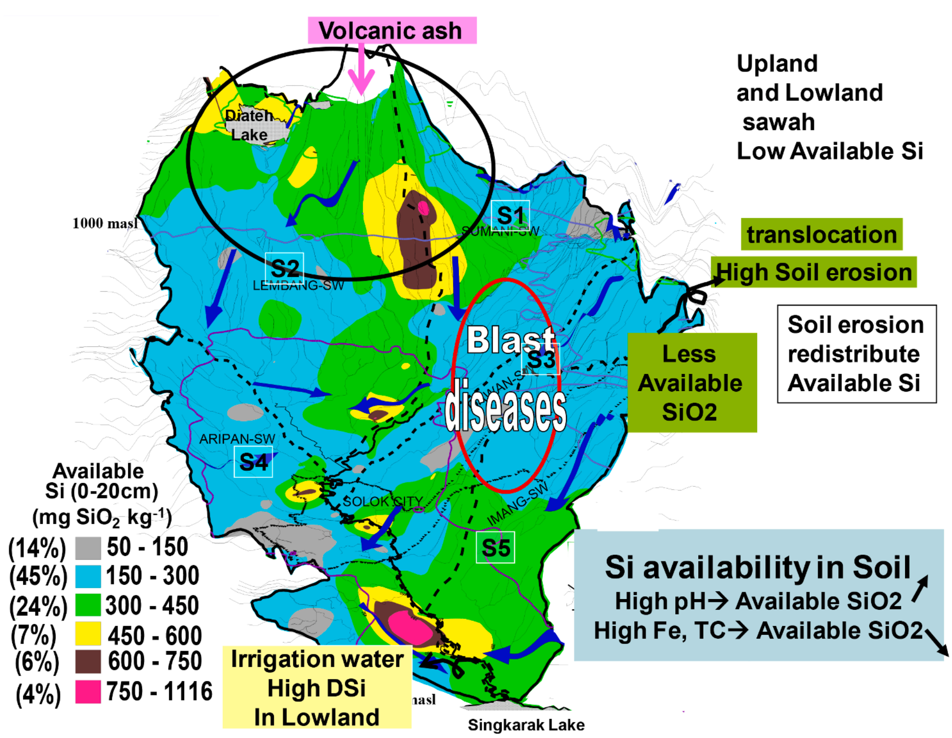

Fig. 9. Diagram of available-Si distribution influenced by various factors.

Table 5
Average Si concentration (mg SiO_2 L^{-1}) in irrigation and river water from Sumani Watershed, Java Island, and other Asian countries.

Study (reference)	Location	Area (km^2)	SiO_2 concentration (mg SiO_2 L^{-1})
Irrigation water in Sumani Watershed (SW)	Sumatera Island, Indonesia	583.3	32.65
River water in Sumani Watershed (SW)	Sumatera Island, Indonesia	583.3	40.94
Lake Dibawah in Sumani Watershed	Sumatera Island, Indonesia		5.96
Irrigation water in Java (Darmawan et al., 2006)	Java Island, Indonesia		14.00
River water in Java (Kawaguchi and Kyuma, 1977)	Java Island, Indonesia		29.82
River water Citarum Watershed (Husnain et al., 2008)	Java Island, Indonesia	6949	24.05
River water Kaligarang Watershed (Husnain et al., 2008)	Java Island, Indonesia	210	37.28
River water in Thailand (Kawaguchi and Kyuma, 1977)	Thailand		17.19
River water in West Malaysia (Kawaguchi and Kyuma, 1977)	Malaysia		13.01
River water in Sri Lanka (Kawaguchi and Kyuma, 1977)	Sri Lanka		13.07
River water in Japan (Kawaguchi and Kyuma, 1977)	Japan		19.00
Irrigation water in Japan (Kumagai et al., 2002)	Japan		10.20

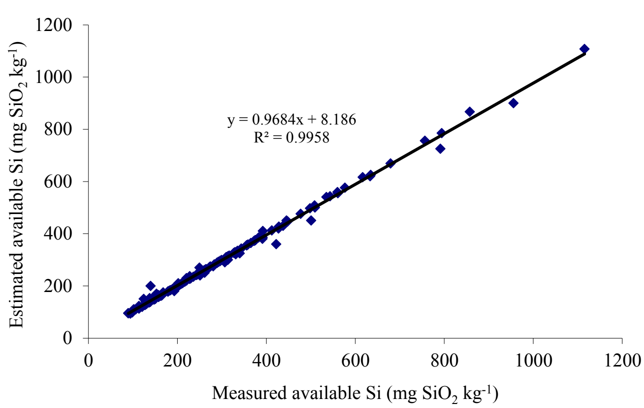

Fig. 10. Correlation between measured available Si in the laboratory and estimated value.

available Si and estimated value) and estimates of available Si. Again, this can be seen easily that the value is distributed around the horizontal straight line which demonstrates that the estimated error value is almost zero. The estimated value of the large error did not depend on the actual estimated values.

4. Discussion

According to Matichenkov and Calvert (2002) and Sumida (1992), available Si at <600 mg SiO_2 kg^{-1} and <300 mg SiO_2 kg^{-1} is considered to be low and deficient, respectively, for growth and rice production. As shown in Table 1, the USLE C factor in the paddy field is the smallest

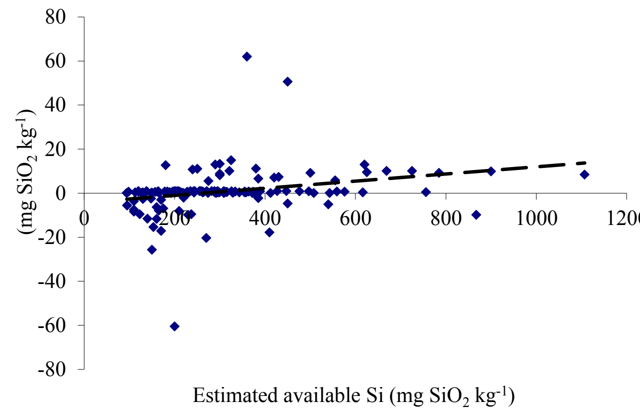

Fig. 11. Correlation between the estimated available Si and estimated error.

value compared with other plants, and the estimated soil erosion is also small. Table 1 shows that the natural causes of erosion in the SW are due to the large R, K and LS values of the USLE factor. Soil erosion in the SW can be controlled by reducing the parameters of USLE C and P factors. In general, Si is available in sawah soils at deficient levels. The erosion status is also low. The available Si in soils ranges from deficient to low levels, indicating that the status of soil erosion in sawah is so low that it does not have a significant effect on the cause of available Si in sawah soils at the level of definition (<262.4 mg SiO_2 kg^{-1}). This means that the available Si is more influenced by the practice of rice management.

Si concentrations are generally available in the SW at low to deficient levels. From 77 samples of sawah soil at a depth of 0–20 cm, 83% concentration of available Si in soils was found at a deficient level, 17% at a low level and 0% at a high level. Deficient levels of available Si in the soil are found in subwatershed Lembang (S2), Sumani (S1), Aripan (S4), Imang (S5) and Gawan (S3). Significant Si deficiency has occurred in the sawah in the SW (Table 1). Thus, adding Si in the form of fertilisers is needed in sawah. The aim is to increase sawah production by more than 5 tons ha^{-1} to 9 tons ha^{-1} (Aflizar et al., 2019).

Table 1 shows that the available Si concentrations in soil > 600 mg SiO_2 kg^{-1} are found in mixed gardens, forests and shrubs in subwatershed Lembang (S2), Sumani (S1) and Aripan (S4) because these plants do not need much Si for production. According to Ma et al. (2007), sawah desperately needs available Si in the soil for growth, production and protection against diseases. Sawah has deficient levels of Si due to intensive rice farming (3 times a year), burning of straw and the absence of Si return in the form of fertiliser to rice fields (Darmawan et al., 2006).

The available Si concentration in sawah, vegetables and shrubs is less than 300 mg SiO_2 kg^{-1}, indicating that the sawah level is deficient. This is a sign why in sawah soils Si deficiency affects production and blast disease (Aflizar et al., 2009), whereas in mixed gardens and forests, vegetables and tea do not show a significant effect because sawah are Si accumulator, whereas other agricultural crops are not.

The concentration of DSi in water in the SW is higher because in SW there is additional Si from volcanic ash of Mount Talang (Fiantis et al., 2010) and warm springs that have high DSi water content, which are located in the highlands of SW (Somura et al., 2017). Therefore, to increase rice production in SW, the Si should be more than 5 tons ha^{-1} to 9 tons ha^{-1}, and blast disease in rice fields should be eliminated. Based on the data in Tables 2 and 5, Si management is needed in sawah soil in the form of Si fertiliser because there is not enough natural contribution of Si from topsoil and DSi from irrigation water, river water and sediments to reach available Si at concentrations of > 600 mg SiO_2 kg^{-1}. To achieve sustainable Si management in sawah, an average addition of Si fertiliser of 165 kg SiO_2 ha^{-1} is required.

At present, the Si deficiency in sawah soils can no longer be improved from natural fertilisers sourced from irrigation water, river water and sediments alone because 60% of the total land in SW suffer from Si deficiency, 31% have low Si levels, and 10% have high Si levels (Table 1 and Fig. 5). The problem of Si deficiency in sawah is very urgent (Table 1 and Fig. 5). Considering that Indonesia's population is increasing every year, the loss of rice fields to non-agricultural uses is high.

Table 3 shows the mean soil properties of the land-use types. According to Bollich and Matichenkov (2002) and Sumida (1992), available Si levels less than 600 and 300 mg SiO_2kg^{-1} are considered to be "low" and "deficient" for rice plant growth. Based on these criteria, most of the sites were grouped into the categories of "low" and "deficient," indicating that soil in the SW was generally low in available Si. This finding may explain the blast diseases frequently observed in this watershed. Tea plantation showed a high TC, and vegetable garden showed a low pH. In the SW, the low Si availability may be associated with the intensive agricultural practices and the absence of additional Si fertilizer by farmers, in addition to the high rainfall that transports Si from the surface soil through erosion and runoff. This region has the annual contribution of volcanic ash from Mt.Talang to the agricultural area on the island of Java as mentioned by Kawaguchi and Kyuma (1977). However, the high activities of rice farming and vegetable and tea planting have resulted in the mining and transport of Si through the process of harvesting (Darmawan et al., 2006).

Referring to Fig. 3, the concentration of hydrogen protons from soil decreased with increased concentrations of Ca, K, and available Si, resulting in increased pH. This process may have occurred throughout the entire SW. To enable the process of release of nutrients needed by plants from volcanic ash, sourcing a substantial amount of hydrogen protons is necessary. In the SW can originate from inorganic acids released from the eruption of Mount Talang which always occurs in small and medium scale in the past until now. In addition, organic acids derived from the exudates of biota can be a source of hydrogen protons (Fiantis et al., 2010; Dahlgren et al., 1999). The weathering of volcanic ash occurs through surface exchange with aqueous hydrogen ions (Shoji et al., 1993). The main sources of protons for the weathering of volcanic ash include acidic aerosols, carbonic and organic acids. Acidic aerosols comprise sulphuric acid (H_2SO_4), hydrochloric acid (HCl), fluoric acid (HF), and nitric acid (HNO_3), which originate from the eruption plume, whereas carbonic and organic acids originate from biota (Dahlgren et al., 1999). Besides an increase in the concentration of silicon in the soil because it deals with pH, Ca and K. extractable Fe and Exchangeable Na is the opposite effect, namely reducing the availability of Si concentration in the soil. The highly extractable Fe showed a negative correlation with Si availability. This finding may have been due to the indirect effect of soil pH, where Fe solubility was high at low pH and the low pH was related to the solubility of Ca, K, and Si. Jansen et al. (2003) reported that the solubility of Fe (III) was higher at pH 4 and 5. Conversely, the solubility of Fe (II) and Al was high at pH 3.5.

Exchangeable Na led to increased concentrations and thus to the low availability of Si. This finding was most likely due to the Na in the form of sodium carbonate (Na_2CO_3) reacting with SiO_2 and the liquid form of sodium silicate (Na_2SiO_3) and CO_2 (Greenwood and Karpinets, 1997). We suspected that Na_2SiO_3 was a form of Si unavailable to plants. Si is available for plants in the form of Si (OH_4) (Saccone et al., 2006), H_4SiO_4 (Tian et al., 2008). The solubility of Si in soil solution ranged from pH 2 to 9, and Si typically comes in the form of orthosilikat. We speculated that Na_2CO_3 formed from the reaction of Na ions with carbonate ions.

Regarding TC, we found no significant correlation for all land-use types. However, when we extracted sawah soil, a negative correlation was found between TC and Si availability. This finding was due to the high TC in sawah soil because of the high rice production. Darmawan et al. (2006) reported that the TC of sawah soil has increased by 13.7% during the 30 years of intensive cultivation of rice in Java, Indonesia. The high production of rice meant that Si was highly consumed. They changed from Si in a form available for plants to be biogenic Si in the form of Si which is not available for plants. Si in the remaining plants so that decomposes organic material is a form of Si which is generally in the form of biogenic Si, which in form is not available as plants (Imaizumi and Yoshida, 1958). Changes in the form of available Si as biogenic Si may explain why soil with high TC had decreased available Si. Darmawan et al. (2006) reported that intensive rice without Si fertilizer and mining Si has resulted in the soil through the process of harvesting. Thus, the availability of Si in sawah in Java soil decreased by 11%–21% within 30 years.

For the hilly areas far from Mount Talang, Figs. 4 and 5 illustrate high soil erosion with low content of Si (upper positions of S2, S3, S4, and S5) and low erosion with relatively high availability of Si (lowlands S1, S2, S3, S4, and S5). Vegetable land mostly had low Si availability (Table 2 and Fig. 3), where the show is located at the highest regional rate of erosions. Severe soil erosion can carry away available Si on the soil surface. Conversely, the availability of Si was relatively high at sawah and generally distributed in the lowlands (Figs. 3 and 4), where most sediment accumulation occurs (Fig. 3). Aflizar et al. (2010) reported the results of the estimation method for the location kriging deposition of eroded in sawah, which numerous eroded soil particles on the topography of the watershed that were transported and accumulated at sawah in the lowlands. At lowland soil layers deeper than the Upland area. We believe that this finding may be due to the accumulation of particles eroded from highlands in the lowlands. Local farmers also believe that the lowlands originated from the eroded soil of the highlands (Personal communication, 2009). Lowland areas of geology data showed that soil derived from basaltic andesite colluvial deposit from Mount Talang in the highlands was transported in large quantities through soil erosion one hundred years ago.

Based on calculations from the data in Table 3 and Fig. 5, the basis for making Si fertiliser recommendations is to achieve an available Si concentration of > 600 mg SiO_2 kg^{-1} in the soil. Thus, the calculation of Si fertiliser is based on 600 mg SiO_2 kg^{-1} reduced by the concentration of Si from Si input from top soil (0–20 cm), irrigation water, river water and sediment. The result of this reduction will be the recommendation of Si fertiliser needed by the soil to reach a concentration of 600 mg SiO_2 kg^{-1} and to produce rice > 5 tons ha^{-1} to 9 tons ha^{-1}. The fertiliser recommendations are obtained based on a 3D map of the distribution of available Si (Fig. 5), which has been mapped: Sawah soil with available Si concentration: Si = 50–150 mg SiO_2 kg^{-1}, then recommended Si fertiliser = 299–236 kg SiO_2 ha^{-1}, Si = 150–300 mg SiO_2 kg^{-1}, then recommended Si fertiliser = 236–141 kg SiO_2 ha^{-1}, Si = 300–450 mg SiO_2 kg^{-1}, then recommended Si fertiliser = 141–47 kg SiO_2 ha^{-1}, Si = 450–600 mg SiO_2 kg^{-1}, then recommended Si fertiliser = 47–0 kg SiO_2 ha^{-1} and Si ≥ 600 mg SiO_2 kg^{-1}, then recommended Si fertiliser = 0 kg SiO_2 ha^{-1}.

However, Si management is sustainable in the paddy fields in SW through the recommendation of balanced Si fertilisation. It can be achieved by paying attention to the high soil erosion status in SW (Fig. 4). In other words, soil erosion in SW must be controlled because it is found in mixed vegetable and mixed gardens in the highlands of SW (Fig. 4), which can cause leaching of Si fertiliser given to the sawah. Therefore, in order to have good Si management, the soil erosion distribution map in Fig. 4 is very useful and can be used as a guide to determine soil and water conservation actions that will be given to the SW. Aflizar and Masunaga (2013) reported that areas that have high soil erosion must be given soil and water conservation in the form of contour plantings and making of terraces. The availability of 3D visual maps of the available Si distribution in the soil and distribution of soil erosion and DSi in irrigation and river water and Si sediment is very helpful for sustainable agricultural development and management of Si in paddy soils. It can also be used to improve the environment on a watershed scale in Indonesia.

5. Conclusions

Soil depth (0–20 cm) and Si from irrigation and sediment was a major source of Si in the SW. Soil erosion transported soil surface rich in

SiO_2, making it available to lowlands sawah. Meanwhile, the river water in the surrounding highlands had high erosion and low SiO_2 availability. Low pH, high extractable Fe, and high exchangeable Na showed relatively low availability of SiO_2. Given these factors, the availability of Si distribution in the SW. When Si availability in sawah soil was low, we found rice blast disease. Generally, Si availability in the SW was low. However, in areas close to Mount Talang, is the height of the addition of SiO_2 from volcanic ash, also in the lowland areas through irrigation water. However, on the west side of the SW, the area we found the availability of SiO_2 sawah deficiency especially at high topography on the west side of the SW, which is now found in many diseases according to the results of interviews with farmers. Blast disease occurred based on our observations but not in the area surrounding Mount Talang. This finding may be due to the contribution of SiO_2 from volcanic ash Mount Talang. For the sake of a sustainable management of watershed, we recommend the addition of SiO_2 to rice fields with doses 230 kg/ha. Possible sources of SiO_2 include coal fly ash because it is so widely available in Indonesia.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Aflizar, A.R., Masunaga, T., 2013. Assessment erosion 3D Hazard with USLE and surfer tool: a case study of Sumani Watershed in West Sumatra Indonesia. J. Trop Soils 18 (1), 81–92.

Aflizar, A., Alarima, C.I., Masunaga, T., 2018. Effect of soil erosion and topography on distribution of cadmium (Cd) in Sumani watershed, West Sumatra, Indonesia. Matec Web of Conferences 229, 03001.

Aflizar, Hasman. E, Agustamar, Irwan. A, Gusmalini, Susena. W, Ismawardi, Erprabawayudha, Idowu C.A. 2019. Soil Suitability Evaluation for Sawah in Sumani Watershed in West Sumatra Indonesia using Surfer Tool. IEEE. Doi:10.1109/iCAST1.2018.8751621.

Aflizar, Saidi, A., Husnain, Hermansah, Darmawan, Harmailis, Soumura, H., Wakatsuki, T. & Masunaga, T. 2010. Characterization of soil erosion status in an agricultural watershed in West Sumatra, Indonesia. Tropics, vol 19.

Ahmadi, S.H., Amin, S., Keshavarzi, A.R., Mirzamostafa, N., 2006. Simulating watershed outlet sediment concentration using the ANSWERS Model by applying two sediment transport capacity equations. Biosyst. Eng. 94, 615–626.

Amore, E., Modica, C., Mark, A., Nearing, N.A., Santoro, V.C., 2004. Scale effect in USLE and WEPP Application for soil erosion computation from three Sicilian basins. J. Hydrol. 293, 100–114.

Balai Penelitian Tanah, 2009. Technical guidelines of soil chemistry analysis, plant, water, and fertilizer [In Indonesia: Petunjuk Teknis Analisis Kimia Tanah, Tanaman, Air, dan Pupuk]. Balai Besar Litbang SDL Pertanian Badan Litbang Pertanian Deptan, Bogor.

Bollich, P.K, Matichenkov, V.V. 2002.Silicon status of selected Lousiana rice and Sugarcane soils. Proceedings of the second Silicon in Agriculture Conference,22-26 August 2002, Tsuruoka, Yamagata, Japan, pp.50-53.

Dahlgren, R.A., Ugolini, F.C., Casey, W.H., 1999. Field weathering rates of Mt.St Helens tephra. Geochem. Cosmochim. Adv. 63, 587–598.

Darmawan, Kyuma, K., Saleh, A., Subagjo, H., Masunaga, T., &Wakatsuki, T. 2006. Effect of long-term intensive rice cultivation on the available silica content of sawah soils: Java Island, Indonesia, Soil Sci. Plant Nutr, 52, 745-753.

Farida, Jeanes, K., Kurniasari, D., Widayati, A., Ekadinata, A., Hadi, D.P., Joshi, L., Deshi. & Suyamto, M.V.N. 2005. Rapid hydrological appraisal (RHA) of Singkarak Lake in the context of Rewarding Upland Poor for Environmental services (RUPES). Available online.:http://www.worldagroforestry.org/sea/Networks/RUPES/download/Annual_Reports/Appendices2005/Appendix4-2_RHA_Singkarak_Report.pdf.

Fiantis, D., Nelson, M., Shamshuddin, J., Goh, T.B., Ranst, E.V., 2010. Leaching experiments in tephra deposits from Talang volcano (West Sumatra), Indonesia. Geoderma. https://doi.org/10.1016/j.geoderma.2010.02.013.

Gee, G.W. & Bauder, J.W. 1986. Particle-size Analysis. In: Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, (eds. Klute, A.), American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin, p. 399-404.

Golden software. Surfer® 8 for windows 2002 Available online Golden, Colorado http://www.goldensoftware.com/products/surfer/surfer.shtml.

Goovaerts, P., 2000. Geostatistical in soil science: state-of-the-art and perspectives. Geoderma 89, 1–45.

Greenwood, D.J., Karpinets, T.V., 1997. Dynamic model for the effects of K fertilizer on crop growth, K-uptake and soil-K in arable cropping. 2. Field test of the model. Soil Use Manage. 13 (4), 184–189.

Hallmark CT, Wilding LP 1982: Silicon. In Methods of Soil Analyses, Part 2, 2nd edn, Agronomy monographs 9, pp 263-273. American Society of Agronomy, Madison, USA.

Hartemink, A.E., 1998. Soil chemical and physical properties as indicators of sustainable land management under sugar cane in Papua New Guinea. Geoderma 85, 283–306.

Husnain, wakatsuki. T., Styorini, D., Hermansah, Sato, K. & Masunaga. T. 2008. Silica availability in soils and river water in two watershed on Java Island, Indonesia. Soil. Sci. Plant. Nutr. 54. 916-927.

IITA 1979: Selected Methods for Soils and Plant Analysis, Manual Series No. 1, IITA, Ibadan, Nigeria, pp. 70.

Imaizumi, K., Yoshida, S., 1958. Edaphological studies on Silicon supplying power of paddy field. Bull. Nah. Inst. Agric. Sci. B8, 261–304.

Jansen, B., Mulder, J., Verstraten, J.M., 2003. Organic complexation of Al and Fe in acidic soil solutions. Anal. Chim. Acta 498 (1–2), 105–117. https://doi.org/10.1016/j.aca.2003.08.054.

Kitanidis, P.K., 1983. Statistical estimation of polynomial generalized covariance functions and hydrologic method. J. Hydrol. Sci. 36 (3), 223–224.

Koyama, T., Sutoh, M., 1987. Simultaneous multi element determination of soils, plant and animal samples by inductively coupled plasma emission spectrophotometry. Jpn. J. Soil Sci. Plant. Nutr. 58 (5), 578–585 (in Japanese).

Kusumandari, A., Mitchell, B.R., 1997. Soil erosion and sediment yield in forest and agroforestry areas in West Java, Indonesia. J. Soil Water Conserv. 52, 376–380.

Kumagai, K., Nakagawa, F., Morioka, M., Nagasawa, K., Sato, Y., Konno, Y., Ueno, M., 2002. The Concentration of Silica in Rice Plant with Reference to the Silica Status in Paddy Field and River Water in Yamagata Prefecture. In: Second Conference Silicon in Agriculture. Tsuruoka, Yamagata, pp. 72–75.

Kawaguchi, K., Kyuma, K., 1977. Paddy soils in Tropical Asia, their material Nature and Fertility. University Press of Hawaii, Honolulu.

Matichenkov, V.V., Calvert, D.V., 2002. Silicon as a beneficial element for sugarcane. J. Am. Soc. Sugarcane Tech. 22, 21–30.

Ma JF, Miyake Y, Takahashi E 2001: Silicon as a beneficial element for crop plants. In Silicon in Agriculture. Eds L.E Datnoff, G.H Snyder and G.H. Korndörfer, pp.17-39. Elsevier, Amsterdam.

Ma, J.F., Naoki, Y., Namiki, M., Kazunori, T., Saeko, K., Toru, F., Maki, K., Masahiro, Y., 2007. An efflux transporter of silicon in rice. Nature 448, 209–212.

McLean EO 1982: Soils pH and lime requirement. In Methods of Soils Analysis, No 9, Part 2. Eds Al Page, H Miller and DR Keeney, pp. 199–209. American Society of Agronomy, Incorporation, Soil Science Society of America, Incorportion Publisher, Madison.

Moehansyah, H., Maheshwari, B.L., Armstrong, J., 2004. Field evaluation of selected soil erosion models for catchment management in Indonesia. Biosyst. Eng. 88, 491–506.

Qafoku, N.P., Van Ranst, E., Noble, A., Baert, G., 2004. Variable charge Soils: their mineralogy. Chem. Manage. Adv. Agronomy. 84, 159–315.

Saccone, L., Conley, D.J., Sauer, D., 2006. Methodologies for amorphous silica analysis. J. Geochem. Expl. 88, 235–238.

Shamshad, A., Leow, C.S., Ramlah, A., Hussin, W.M.A.W., Sanusi, S.A.M., 2008. Applications of Ann AGNPS model for soil loss estimation and nutrient loading for Malaysian condition. Int. J. Appl. Earth Obs. Geoinf. 10, 239–252.

Shoji, S., Narzyo, M., Dahlgren, R.A., 1993. Volcanic Ash Soil Genesis, Properties and Utilization. Elsevier, Amsterdam, the Netherlands, p. 288.

Somura. H, Darmawan, Sato. K, Ueno M, Husnain, Aflizar and Masunaga T. 2006. Characteristics and Potential Usage of Dissolved Silica in Rice Cultivation in Sumani Watershed, Sumatra, Indonesia. Pertanika J. Trop. Agric. Sci. 39 (4). 601-615.

Sumida, H., 1992. Silicon supplying capacity of paddy soils and characteristics of silicon uptake by rice plants in cool regions in Japan, Tohoku. Agric. Exp. Stn. 85, 1–46.

Thomas, G.W. 1982. Exchangeable cation. In methods of soils analysis, number 9, part 2. ed all page, pp. 159-165. ASA, SSSA, Madison.

THEODOSSIOU, N., & LATINOPOULOS, P. (2007). Corrigendum to "Evaluation and optimisation of groundwater observation networks using the Kriging methodology" [Environ. Model. Softw. (2006) 991–1000]. Environmental Modelling & Software, 22(3), 414–414. doi:10.1016/j.envsoft.2006.07.001.

Veihe, A., 2002. The spatial variability of erodibility and its relation to soil types: a study from northern Ghana. Geoderma 106 (1–2), 101–120.

Walling, D.E., He, Q., Whelan, P.A., 2003. Using 137 Cs measurement to validate the application of the AGNPS and ANSWERS erosion and sediment yield models in two small Devon catchments. Soil Tillage Res. 69, 27–43.

Wang, Y., Zhang, X., Huang, C., 2009. Spatial variability of soil total nitrogen and soil total phosphorus under different land uses in a small watershed on the Loess Plateau, China. Geoderma 150, 141–149.

Warsi, O.M., Dykhuizen, D.E., 2017. Evolutionary implications of Liebig's law of the minimum: selestion under low concentration of two nonsubstitutable nutrients. Ecol. Evol. 7, 5296–5309.

Wischmeier, W.H. & Smith, D.D. 1978. Predicting rainfall erosion losses: a guide to conservation farming, USDA Handbook: No. 537 US Department of Agriculture, Washington, DC. p 1-58.

Wu, L., Beard, B.L., Roden, E.E., Johnson, C.M., 2009. Influence of pH and dissolved Si on Fe isotope fractionation during dissimilatory microbial reduction of hematite. Geochim. Cosmochim. Acta 73, 5584–5599.