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Exchangeable silicon content of soil in a long-term fertilization experiment

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ABSTRACT

Based on a long-term fertilization experiment on a light soil, a study was conducted on the impact of varied fertilization on the levels of silicon forms available in the soil. It was shown that the exchangeable silicon content in the tested soil was very low, which can have a limiting effect on crop yields. Soil pH is a factor that significantly affects the exchangeable silicon content of the soil. Therefore, under the conditions of acidic soils, liming is a treatment that increases the level of silicon forms available to plants in the soil.

Keywords: silicon; mineral fertilization; crop rotation; farmyard manure

The silicon (Si) content of soils, depending on the type of the parent rock, ranges from 1–45% (Sommer et al. 2006). The form readily available to plants is its active form in the soil solution, where this element is present at a concentration of 0.1 to 0.6 mmol/dm^3 (Epstein 1994).

Crop plants take up much larger amounts of silicon than plants growing in natural ecosystems. Seven out of the 10 most important crop plants in the world are counted among the bio-accumulators of silicon (Guntzer et al. 2012a). These plants contain more than 1% Si in dry matter. Guntzer et al. (2012a) have shown that under production conditions the silicon balance is disturbed. The amounts of this element removed with the crops are greater than those supplied to the soil in agricultural ecosystems. The amounts of silicon entering the soil from natural sources do not compensate for the amounts of this element collected from the field with the crop. Consequently, it is observed that the amount of silicon available in the soil is systematically being reduced, which may have a significantly limiting effect on crop yield, especially in cereals (Matichenkov 2008, Bocharnikova and Matichenkov 2012).

The aim of the study was to determine the exchangeable silicon content of the soil depending on varied long-term fertilization.

MATERIAL AND METHODS

The study was conducted on the basis of a long-term fertilization experiment at the Experimental Station of the Faculty of Agriculture and Biology in Skierniewice, Poland. This experiment was established in 1923, in a randomised block design with four replications, on a podsolic soil with a granulometric composition corresponding to slightly loamy sand (particle size distribution: < 0.002 mm – 7%; 0.002–0.05 mm – 6%; > 0.05 mm – 87%). The soil is developed from sandy loam. The selected soil properties are shown in Table 1. The experiment is conducted in a four-field crop rotation system: potatoes, oats, rye and spring barley. The experiment includes the following fertilization combinations: 0; CaNPK; NPK; NP; NK and PK in combinations with or without manure. Mineral fertilization is applied in doses of 90 kg N/ha in the form of ammonium nitrate,

Table 1. Selected soil properties in field experiment

Fertilization	Soil property	0	CaNPK	NPK	NK	PK	NP
M	pH	4.0	6.8	3.8	3.6	3.9	3.6
	C_{org} (g/kg)	4.7	5.3	5.3	5.2	5.0	5.1
	P (mg/kg)	38.6	93.4	104.5	27.8	109.1	102.8
	Al (mg/kg)	9.4	2.2	86.0	102.7	44.2	95.4
M + FYM	pH	4.7	6.0	3.7	3.7	3.9	3.6
	C_{org} (g/kg)	5.5	6.2	6.1	6.1	5.7	5.8
	P (mg/kg)	75.5	119.1	122.0	35.5	117.0	104.1
	Al (mg/kg)	1.4	1.4	73.4	87.0	40.5	66.2

M – mineral fertilization; M + FYM – mineral fertilization with farmyard manure

26 kg P/ha in the form of triple superphosphate, and 91 kg K/ha in the form of a high-potassium salt per year. Every four years, liming is applied at a rate of 1.14 t Ca/ha and manure at 30 t/ha.

For three years (2011–2013) in early spring, soil samples for testing were collected from the top layer of soil (0–20 cm) using Egner's soil sampling stick, taking five sub-samples from each plot and then mixing them into a bulk sample. Each year, they collected 36 soil samples. The collected samples were air-dried, soil was then crushed and sieved through a sieve with a mesh diameter of 2 mm.

Chemical analyses of the soil samples included:
- pH – by potentiometric method after extraction in 1 mol/L KCl (10 g of soil was suspended in 25 mL of KCl and left for 24 h to equilibrate), using a pH meter (Schott, Mainz, Germany) with a glass electrode (PN-ISO 10390, 1997),
- available phosphorus content by the Egner-Riehm method – DL (PN-R-04023, 1996),
- exchangeable aluminum content after extraction in 1 mol/L KCl (60 g of soil was shaken with 150 mL KCl on a rotary shaker for 1 h at 120 rounds per min) with the use atomic absorption spectrometry (AAS) with a ThermoElementar apparatus, Cambridge, UK),
- determination of exchangeable silicon content after extraction in 0.5 mol/L ammonium acetate – by atomic absorption spectrometry with a ThermoElementar.

The results were statistically analysed with ANOVA and with simple regression and correlation at a significance level $P = 0.05$ using Statistica PL software (Tulsa, USA).

The results shown in the tables and figures are the average of three years (2011–2013).

RESULTS AND DISCUSSION

The exchangeable silicon content of the soil ranged from 16.05–36.89 mg/kg (Table 2).

The lowest amounts of this element were recorded in the NK and NP combinations characterized by a strongly acidic reaction. In the combination with full mineral fertilization (CaNPK), regardless of the use of manure, significantly greater amounts of exchangeable silicon in relation to the other fertilization combinations were recorded. These amounts of exchangeable silicon were very low. Although the maximum adsorption of silicon is at pH 9.8, most soils, in which Si is deficient are in the pH range of 5–6 because leaching of silicic acid from soils is a common phenomenon (Frings et al. 2014). According to Matichenkov (2008), there is a critical deficiency of this element in that soil. In such conditions, the silicon deficiency may have a limiting effect on crop yields. Consequently, it is necessary to fertilize with this element in excess of the nutritional requirements of the crop plants.

Silicon is an element whose amounts in available forms in the soil depend on soil pH and exchangeable aluminium content (Figures 1–2).

With an increase in soil pH, the exchangeable silicon content significantly increased. Silicate can

Table 2. Content of exchangeable silicon in soil

Fertilization	0	CaNPK	NPK	NK	PK	NP
	(mg/kg)					
M	28.55	36.89	21.19	16.06	19.07	16.05
M + FYM	26.80	32.88	21.22	18.54	18.29	17.16
$LSD_{0.05}$	6.876					

M – mineral fertilization; M + FYM – mineral fertilization with farmyard manure; *LSD* – low significant difference

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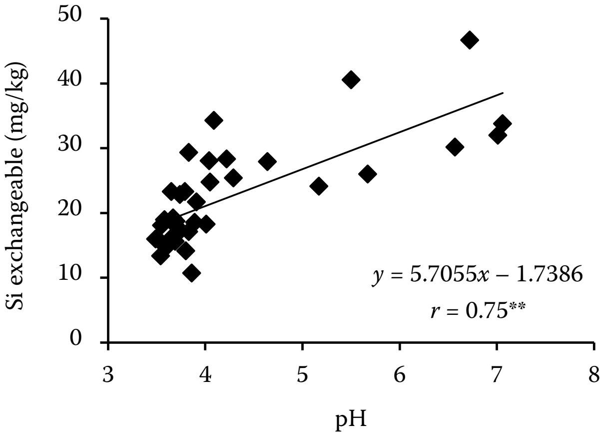

Figure 1. Relationship between pH and exchangeable silicon (Si) content in the soil

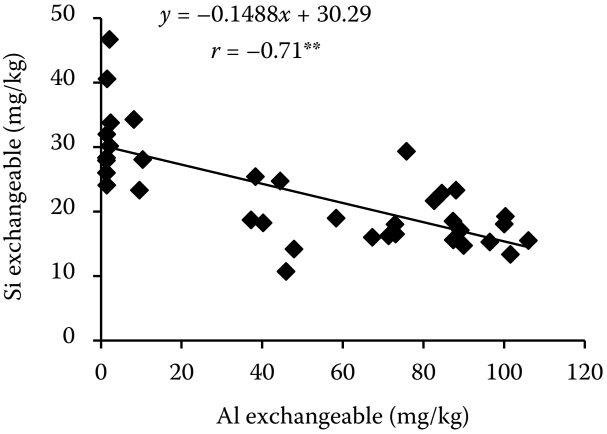

Figure 2. Relationship between exchangeable silicon (Si) and aluminium (Al) content in the soil

be adsorbed to the surfaces of variably charged soil colloids such as Fe and Al hydrous oxides. Such adsorption is highly pH-dependent because with increasing pH (up to pH 9.8; the pK1 for silicic acid) an increasing proportion of total Si in solution is present as H_3SiO_4 rather than H_4SiO_4. Because Si is preferentially adsorbed in the anionic $H_3SiO_4^-$ form, maximum Si adsorption occurs at a soil pH of about 9.8 (Haynes 2014).

At the same time, with increasing levels of exchangeable aluminium, the level of the tested form of silicon in the soil decreased significantly. The soil pH may have indirectly affected the increase in the availability of this element by limiting the occurrence in the soil of exchangeable aluminium, which has a high affinity for silicon and readily enters into chemical reactions with it. Precipitation of silicon-aluminium salts in an acidic environment reduces the amount of exchangeable silicon in the soil. The aluminium-silicate complexes (HAS) forming under acidic conditions in mineral soils account for about 10% of aluminium speciation in the environment (Grenda and Skowrońska 2004, Sommer et al. 2006). Adsorption of silicic acid by aluminium and iron oxides increases with increasing pH in the range 4–9. Aluminium oxides are more effective in the adsorption of silicic acid compared with iron oxides (Cornelis et al. 2011). Kaczorek and Sommer (2004) have shown that under the conditions of soil acidification, the amount of free silica increases. Similarly, Höhn et al. (2008) reported an increase in the amount of silicon available in the soil with a decrease in pH. According to Miles et al. (2014) where a large group of soils in a region of a country is surveyed, there is generally a positive relationship between pH and Si solubility/extractability.

In the case of well-maintained soils, which in terms of the levels of the available forms of soil phosphorus are still in a high-fertility class, one can expect greater amounts of silicon being available to plants. Phosphorus, by reacting with such metals as aluminium and iron, reduces the sorption of silicon. For this reason, silicon becomes more readily available in the soil environment and can potentially be taken up by plants. Lee and Kim (2007) have shown in their studies that the adsorption of phosphates in soils of acidic and neutral pH is higher than of silicates, which indirectly increases the concentration of silicon in the soil solution. In this study, there was no significant relationship between the available phosphorus content and exchangeable silicon content of the soil (Figure 3).

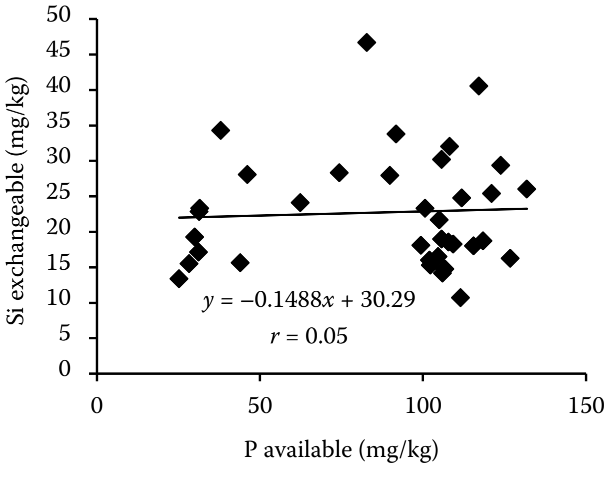

Figure 3. Relationship between the content of available phosphorus (P) and exchangeable silicon (Si) in soil

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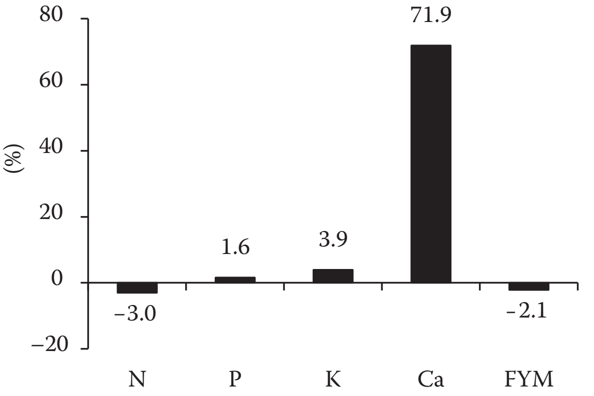

Figure 4. Effect of fertilization on exchangeable silicon (Si) content in the soil

The main effects are moderate increase or decrease of the amounts of various silicon forms in all the combinations fertilized with a given component (N, P, K, Ca, or manure) in comparison with the experimental plots without that component. Mineral and organic fertilization modified the exchangeable silicon content of the soil to a small extent (Figure 4).

Only under the influence of liming there was a significant increase in this form of silicon in the soil (71.9%). Also Guntzer et al. (2012b), in their long-term experiments conducted at Rothamsted, demonstrated that liming significantly increases the amounts of the available forms of silicon in the soil. By comparison, Kim et al. (2010) showed that long-term mineral and organic fertilization in the absence of liming did not affect the available silicon content of a sandy soil over a 56-year period.

In summary, it can be concluded that on the tested experimental plots there was a critical deficiency of silicon available to plants, which could adversely affect crop yields. Consequently, it is necessary to introduce fertilization with this element at rates in excess of the nutritional requirements of the crop plants. Soil pH is a factor significantly affecting the exchangeable silicon content of the soil. Therefore, under the conditions of acidic soils, liming is a treatment that increases the levels of the silicon forms potentially available to plants in the soil.

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