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Plant available silicon in differentiated fertilizing conditions

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Abstract: Based on a long-term fertilization experiment on sandy soil, research concerning the effect of variable fertilization on the soil content of silicon extracted by $CaCl_2$ solution was performed. The content of plant available silicon was evidenced to depend on the applied fertilization and soil properties. Plant silicon supply coefficient varied depending on the fertiliser combination. In the case of potatoes this coefficient was smaller then 1 but for oat was usually higher then one. It suggesting that the amount of available silicon in soil is sufficient to cover the nutritional needs of potatoes but not sufficient for oat.

Keywords: plant-available silicon; mineral fertilisation; manure; stress tolerance

Silicon (Si) is the second most abundant element in the Earth's crust. Its content in soils varies from 200 g Si/kg in silty soils to 450 g Si/kg in sandy soils (Tubana et al. 2016). The availability of the element for plants, however, is strongly dependent on soil properties affecting the processes of sorption and desorption of Si, and particularly on soil pH. The content of plant-available silicon varies from 3×10^{-3} to 4.5×10^{-3} g Si/kg of soil (Liang et al. 2015a). Silicon is included to a group of elements with a positive effect on the growth and development of many plant species, particularly increasing their resistance to biotic and abiotic stress (Yan et al. 2018, Coskun et al. 2019). Many studies also evidenced that some plants, e.g., rice, sugarcane, wheat, soy, potatoes, or oat respond to fertilization with the element with yield surplus (Vulavala et al. 2016, Artyszak 2018, Yan et al. 2018). As evidenced by Klotzbücher et al. (2018), mineral and organic fertilization can affect the content of available silicon in soil primarily through the effect of soil pH. Soil reaction has a considerable impact on the rate of the process of weathering of soil minerals, as well as on the processes of sorption-desorption of Si and solubility of phytolites that determine the amount of available silicon in the soil. Due to this, research has been undertaken aimed at the determination of the amount of plant available silicon (extracted with 0.01 mol/L of $CaCl_2$) in the soil in conditions of long-term unsustainable fertilization on sandy soil, and determination of the degree of supply of selected crops with the element.

MATERIAL AND METHODS

The conducted research was based on a permanent fertilization experiment located in the Experimental Station of the Faculty of Agriculture and Biology of the Warsaw University of Life Sciences in Skierniewice (51°57'N, 20°9'E). The experiment was established in 1923 using the method of random blocks in four repetitions on Luvisol (WRB 2014). The basic properties of the soil are presented in Table 1. The research has continued uninterruptedly until today. The experiment is conducted in 4-field rotation with the following crops: potatoes, oat, rye, and spring barley. The experiment covers the following fertilizer combinations: 0, CaNPK, NPK, NP, NK, and PK in the conditions of application of manure and without manure. Mineral fertilisation is applied in doses of 90 kg N/ha in the form of ammonium nitrate, 26 kg P/ha in the form of triple superphosphate, and 91 kg K/ha in the form of high-percentage potassium salt

Table 1. Soil properties in the field experiment

	Mineral fertilization						Mineral fertilisation with farmyard manure					
	0	CaNPK	NPK	NK	PK	NP	0	CaNPK	NPK	NK	PK	NP
pH	3.97	6.78	3.82	3.58	3.95	3.59	4.68	6.06	3.73	3.75	3.95	3.59
Organic carbon (g/kg)	4.69	5.34	5.34	5.20	5.01	5.10	5.50	6.23	6.14	6.10	5.74	5.80
P	38.6	93.4	104.5	27.8	109.1	102.8	75.5	119.1	122.0	35.5	117.0	104.1
K (mg/kg)	40.9	168.0	164.3	160.5	178.9	38.8	110.1	172.1	163.4	165.4	186.1	46.4
Al	9.37	2.23	86.01	102.66	44.21	95.49	1.42	1.44	73.38	87.05	40.53	66.25

annually. Every four years, liming is applied in a dose of 1.14 t Ca/ha, and manure in a dose of 30 t/ha. Soil samples for the study were collected in early spring from the surface soil layer (0–20 cm) using stainless steel soil sampling probe. The soil samples were air dried and sieved to < 2 mm. The soil samples were characterised for: pH – by the potentiometric method after extraction with 1 mol/L KCl (ISO 10390, 2005), total organic carbon after dry combustion (ISO 10694, 1995), available P and K by the Egner-Riehm (DL) method (PN-R-04023, 1996, PN-R-04022, 1996), active Si in soil solution and available Si after extraction with 0.01 mol/L $CaCl_2$ (Sauer et al. 2006), and available aluminium after extraction with 1 mol/L KCl (McLean 1965). The studied plant materials were potatoes of the Hermes cultivar (tubers), and oat of the Dragon cultivar (grain and straw). Silicon content was determined using ICP method (IRYS Advantage ThermoElementar, Cambridge, UK) after wet mineralisation in a closed system in a microwave (Ethos Up, Milestone INC, Shelton, USA) (10 cm^3 of a mixture of concentrated acids HNO_3 and $HClO_4$ was added to 0.3 g of plant material in a ratio of 5:2, and mineralised for a period of 0.5 h).

In the paper were evaluated following parameters:

(1) Effects of the application of particular fertilizer components on an increase/decrease in silicon content in soil, based on the following formula:

$$E_x = [(\text{Si content in soil from objects with application of element } x / \text{Si content in soil from objects without the application of element } x] \times 100\%$$

Where: E_x – percent increase or decrease in Si content in soil under fertilization with component x; x – fertilizer component/fertilization (N, P, K, Ca, manure).

(2) Potential of soil to supply specific crop with bioavailable silicon was calculated using the following coefficient: plant silicon supply coefficient (PSSC):

$$PSSC = \frac{\text{Silicon uptake by a plant (kg/ha)}}{\text{Content of available silicon in soil (kg/ha)}}$$

For statistical processing of the obtaining results, the multi-factor analysis of variance and the linear regression method was applied. The determination of the significance of differences between mean values was employed a Tukey's test, at a significance level $P = 0.05$. The statistical analysis of results was performed with the application of Statistica ver. 10 software (Krakow. Poland).

RESULTS AND DISCUSSION

The content of available silicon in the soil was dependent both on soil properties and applied fertilization level in the experiment varied from 4.90 to 13.63 mg/kg. The lowest content of the element was observed on combination NK with manure and the highest on combination with full mineral fertilization with manure (CaNPK + manure) (Table 2). Our experiment showed that silicon content in soil was dependent on the pH and exchangeable aluminum, and on a lower degree on the content of available phosphorus (Figure 1). With an increase of pH values in the soil, a significant increase in the soil content of silicon extracted with

Table 2. Soil content of available silicon depending on fertilization (mg/kg)

Fertilization system	0	CaNPK	NPK	NK	PK	NP
M	7.03^{b}	13.04^{d}	6.12^{ab}	4.90^{ab}	8.34^{b}	5.35^{a}
M + FYM	10.11^{c}	13.63^{d}	7.03^{b}	6.37^{a}	9.56^{bc}	5.41^{a}

M – mineral fertilization; FYM – farmyard manure. Different letters mean significant difference at $P \leq 0.05$

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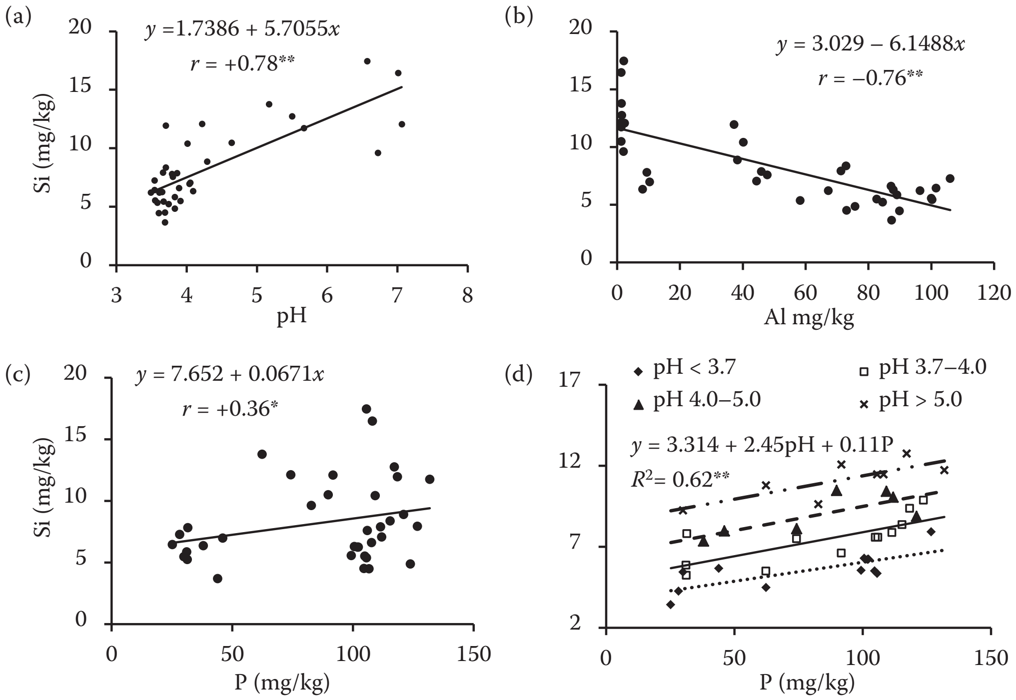

Figure 1. Dependency between soil content of available silicon and (a) soil pH; (b) the content of exchangeable aluminum; (c) the content of available phosphorus, and (d) content of available phosphorus in the soil and soil pH. **P* < 0.05; ***P* < 0.01

$CaCl_2$ solution (r = +0.78) was observed. An increase in the content of exchangeable aluminum in the soil caused a substantial decrease in the content of available silicon (r = –0.76). With an increase in the content of available phosphorus, the content of available silicon in soil increases (r = 0.36), but this relation was not dependent on soil pH because the regression lines were parallel (Figure 1d). According to Haynes (2014) and Miles et al. (2014), pH is a dominant factor determining the content of available silicon in soil to the greatest degree through the effect of the rate of weathering process of soil minerals releasing Si to the environment, and reactions of precipitation and adsorption of silicates on soil colloids and hydrous iron and aluminium oxides. The application effects of particular fertiliser components on an increase or decrease in soil content of silicon (E_x – calculated according to formula 1), show that lack of one elements in a fertiliser dose, e.g. lack of liming or application of manure, causes changes in the content of silicon in soil (Figure 2). Kim et al. (2010) evidenced that long-term mineral and organic fertilization over 56 years on sandy soil did not affect the content of available silicon in the soil. Among the fertilizer compounds analyzed in our study, liming had the strongest effect on an increase of available silicon content in soil, but fertilization with nitrogen the decreased of the Si content in the soil. A positive effect on available silicon content in soil was also observed in the case of fertilisation with phosphorus, potassium, and application of manure (Figure 2). Under the influence of nitrogen fertilization, the content of silicon in the soil decreased by more than 16% about objects in which fertilization with this element was not used (Figure 2). These results are in accordance with research by Beard et al. (2018), and Keeping et al. (2015), who determined that the application of N at a higher ratio of NH_4^+ to NO_3^- reduces soil pH, contributing to a decrease in the amount of silicon available for plants, extracted with $CaCl_2$. Fertilization with phosphorus caused the

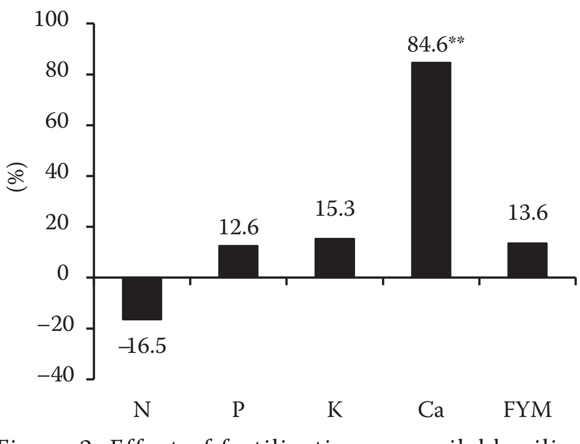

Figure 2. Effect of fertilization on available silicon content in soil (E_x). FYM – farmyard manure

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Table 3. Yield and silicon (Si) content in plant

			0	CaNPK	NPK	NK	PK	NP
Yield (t/ha)	oat grain	M	0.88^{c}	2.33^{g}	1.37^{e}	0.13^{a}	1.21^{d}	0.45^{b}
		M + FYM	1.60^{f}	2.55^{g}	1.59^{f}	1.33^{e}	1.41^{e}	1.14^{d}
	oat straw	M	0.92^{c}	2.65^{g}	1.44^{d}	0.15^{a}	1.37^{d}	0.51^{b}
		M + FYM	1.98^{f}	2.88^{g}	1.57^{e}	1.60^{e}	1.65^{e}	1.40^{d}
	potatoes tubers	M	2.09^{a}	5.19^{e}	4.37^{d}	1.32^{a}	2.32^{b}	2.33^{b}
		M + FYM	3.88^{c}	6.29^{f}	4.78^{d}	5.09^{d}	4.30^{d}	4.80^{d}
Si content (mg/kg)	oat grain	M	6.24^{b}	7.25^{c}	6.33^{b}	4.82^{a}	6.91^{bc}	5.33^{a}
		M + FYM	5.49^{a}	8.69^{e}	5.66^{ab}	5.84^{b}	7.62^{d}	5.69^{ab}
	oat straw	M	11.48^{a}	16.51^{d}	10.66^{a}	9.64^{a}	13.82^{c}	11.45^{a}
		M + FYM	12.98^{b}	16.38^{d}	11.32^{a}	11.69^{ab}	14.23^{c}	13.93^{c}
	potatoes tubers	M	0.32^{b}	0.58^{g}	0.36^{c}	0.38^{d}	0.27^{a}	0.39^{d}
		M + FYM	0.56^{g}	0.56^{g}	0.43^{e}	0.48^{f}	0.45^{e}	0.33^{b}

M – mineral fertilization; FYM – farmyard manure. Different letters mean significant difference at $P \leq 0.05$

increase of Si available in soil by more than 12% about objects not fertilized with this component (Figure 2). Phosphorus fertilization can increase the amount of available silicon in soil because phosphates strongly displace silicates from the solid phase to the soil solution (Phonde et al. 2014). Lee and Kim (2007) showed that adsorption of phosphates in soils with acidic and neutral reaction is higher than that of silicates, which directly contributes to an increase in the concentration of silicon in the soil solution. Our study shows no effect of long-term fertilization with potassium on the content of available silicon (Figure 2). Phonde et al. (2014) evidenced that the content of silicon extracted with $CaCl_2$ solution was negatively correlated with the soil content of available potassium. The long-term farmyard manure application increased available silicon content by about 14% about objects without manure (Figure 2). The application of manure increases the amount of organic matter in the soil, determining silicon content in soil (Tubana et al. 2016). Song et al. (2015) also evidenced that the long-term application of organic fertilizers contributes to an increase in the soil content of available silicon. Due to long-term liming, the content of available silicon in soil increased by approximately 85% in comparison to objects not limed (Figure 2). In long-term experiments conducted in Rothamsted, Guntzer et al. (2012b) evidenced that liming has a considerable effect on an increase in the number of available forms of silicon in the soil.

Silicon content in plants varied depending on soil properties and the applied fertilization and was the highest in the condition of liming and application of manure (CaNPK and CaNPK + manure) (Table 3). The comparison of the analyzed plants showed that the highest silicon content concerned oat straw, and the lowest – potatoes. Cereals belong to plants from a group accumulating higher amounts of silicon than dicotyledonous plants. Silicon content in cereals can vary from 1% to 3% of dry mass, whereas potatoes are among plants accumulating less than 0.5% of silicon in dry mass (Guntzer et al. 2012a). Plants from family Graminae developed special mechanisms controlling the uptake of the element among cereals, oat belongs to specific bio accumulators of silicon because it uptakes silicon from the soil solution in an active way (Liang et al. 2015b). The amount of available silicon in the soil exceeded the nutritional needs of potatoes multiple times (6–30 times; Table 4). Plant silicon supply coefficient for potatoes varied depending on the fertilizer combination from 0.03 to 0.17. In the case of oat, the coefficient value was from 3 to 24 times higher in comparison to potatoes. The value of the coefficient always remained higher in the case of combinations with manure in comparison to exclusively mineral fertilization. In combinations CaNPK, NPK, and PK, the PPSC for oat adopted values > 1, suggesting that the amount of available silicon in soil is not sufficient to cover the nutritional needs of oat.

Available silicon content was dependent on soil properties and long-term differentiated fertilization. The highest content of available silicon in the soil was observed for a combination with entirely mineral fertilization (CaNPK), and the lowest for combination NK without liming. Liming and organic fertilization increased the content of available silicon in the soil. With an increase in soil pH, a considerable increase in

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Table 4. Plant silicon supply coefficient

	0	CaNPK	NPK	NK	PK	NP
Oat						
M	0.8^{c}	1.5^{e}	1.3^{d}	0.1^{a}	1.5^{e}	0.5^{b}
M + FYM	0.9^{c}	1.7^{ef}	1.3^{d}	1.8^{f}	1.2^{d}	1.6^{e}
Potatoes						
M	0.03^{a}	0.08^{c}	0.09^{c}	0.03^{a}	0.03^{a}	0.06^{b}
M + FYM	0.06^{b}	0.07^{bc}	0.10^{d}	0.17^{e}	0.07^{bc}	0.10^{d}

M – mineral fertilization; FYM – farmyard manure. Different letters mean significant difference at $P \leq 0.05$

the content of silicon extracted with $CaCl_2$ solution was observed, and an increase in the content of exchangeable aluminum in the soil caused a considerable decrease in the content of available silicon. The amount of silicon released to the soil solution depends on the content of phosphorus and increases with an increase in the soil content of available phosphorus. The amount of available silicon in the soil exceeded the nutritional needs of potatoes multiple times. These suggests small nutritional requirements of the plant towards silicon. The nutritional needs of oat towards silicon are multiple times higher, and the amount of available silicon in soil is usually not sufficient to cover them.

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