

Spatial Heterogeneity of Soil Silicon in Ukrainian Phaozems and Chernozems

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ABSTRACT

This study investigated the spatial variability of the soil silicon content in relation with topography, parent materials, soil texture, soil organic matter, exchangeable cations and pH. Using the experimental data from two longterm sites in the Forest-Steppe area of Ukraine, the SiO₂ content was estimated in 60 samples taken from a soil depth 0–25 cm. The accumulation of SiO₂ was significantly greater in the soils formed in footslopes. A content of extractable silicon fraction significantly increased from a sandy loam- (366–465 mg·kg⁻¹) to medium- (670–697 mg·kg⁻¹) and heavy- (506–849 mg·kg⁻¹) textured soils. The highest amount of available silicon content was found in the soils containing: 35.0–39.9% of physical clay fraction (< 0.01 mm dia) in Hrytsiv area – 143.0 ± 46 mg·kg⁻¹ and < 25.0% of physical clay fraction in Khrolyn area – 125.0 ± 6 mg·kg⁻¹. A significant relationship was found between pH_{KCl}, P₂O₅, K₂O, Mg and both forms of SiO₂. There was almost no correlation between available/ extractable SiO₂ and exchangeable Ca and ∑ Ca+Mg. Our studies found the best correlation between extractable SiO₂ and spring barley yield (r = 0.651; P = 0.041), as well as soluble SiO₂ and corn for grain yield (r = 0.514; P = 0.128). No significant relationships were found for sugar beet, winter wheat, sunflower.

Keywords: silicon, chernozem, fertilization, exchangeable cations, pH, soil texture

INTRODUCTION

The study of silicon in the pedosphere expands the possibilities of agronomy and relevant agricultural practices. Modern scientific research is aimed at determining the content of silicon compounds in plants, soils, establishing its critical levels in plants and soils, procedures for assessing the silicon available to plants, and the study of potential sources of silicon for agricultural production. Numerous studies have established the positive role of silicon in plant metabolism, the growth of their biomass due to the accelerated synthesis of the silicon-containing organic compounds [Richmond and Sussman, 2003]. Other authors point to the prominent role of silicon in counteracting biotic (herbivory and pathogen)

and abiotic (metal toxicity) plant stresses [Epstein, 1994; Jones & Handreck, 1967]. Silicon fertilizer for industrial and grain crops can increase their yields by 21–44% [Raleigh, 1939; Lipman, 1938; Sommer, 1926; Conner, 1921]. With the intensification of agricultural production, in addition to the basic elements, i.e. nitrogen, phosphorus, potassium, the importance of which for crop yields is recognized, much attention was paid to secondary and trace elements, in particular, silicon [Bykova et al., 2020]. In some regions, fertilizing the soil with the silicon-containing materials is becoming standard agricultural practice for growing rice, sugar cane, sugar beet.

At the same time, the lack of sufficient information on the spatial provision of soils with the available forms of silicon slows down the

introduction of silicon materials into the system of agricultural crops fertilization. In this regard, we conducted research to study the relationship of different forms of silicon with soil and relief, particle size distribution of the soil, the composition of exchangeable cations, and the soil pH.

Silicon is the second most abundant element of the Earth's crust after oxygen in terms of mass and quantity. Its content in the Earth's crust is 27.6% of its mass [Nedukha, 2019]. Due to the fact that the chemical composition of soils is determined by the elemental composition of the zone of hypergenesis, the concentration of silicon in the solid phase can vary from <1% to more than 45%, depending on the soil-forming rock. The mechanical elements of soils of sandy granulometric composition (sod, sod-podzolic, alluvial) can consist of SiO_2 in almost 100%, while in organogenic soil horizons, the content of SiO_2 may not exceed one percent [Orlov et al., 2005]. In soils, silicon is represented by free compounds SiO_2 (quartz, chalcedony, opal) and salts of silicic acids (silicates). Molecules of ortho- and polysilicic acids are present in soil solutions. In the solid state, SiO_2 is a part of such minerals as: montmorillonite (51.1%), kaolinite (45.4%), illite (49.3%), vermiculite (35.9%), chlorite (26.7%). The SiO_2 content in loesses can vary from 51.7 to 76.0% [Samofalova, 2009]. Increased SiO_2 content in soils may be associated with silica dehydration, acid reaction and mineral adsorption [Landré et al., 2020].

Silicon is a constitutional element of flora and fauna. In 1814, G. Dewey, considering the role of silicon in the construction of the skeletal framework of plants, hypothesized the mineral nutrition of plants with silicon. In 1856, Liebig established the research on the introduction of sodium silicate as a fertilizer and formed a quartet of macronutrients (N, P, K, Si), which are of paramount importance in plant nutrition [Kozlov et al., 2015; Rothamsted, 1992; Tonkha, 2018]. Later, Maxwell (1898) and Hall and Morison (1906) based on the results of field experiments on the availability of silicon compounds in agriculture. Plant studies offered to use them as fertilizer. According to the results of the field research conducted by scientists in the tropics [Onodera, 1917; Miyake & Adachi, 1922; Yoshida et al., 1959; Anderson, 1991; Long et al., 2018], it was recommended to use silicon fertilizer for growing rice, sugar canes, sugar beets, kiwi, some cereals. Guntzer et al. (2012) noted the important role

of silicon in maintaining the productivity of corn and wheat. The oldest spore plants have the highest content of silicon in the dry matter: horsetail (9%), fern and moss (> 6%). Field crops with high content of silicon include wheat, oats, barley, rice, millet, sugar beets [Voronkov & Kuznetsov, 1984]. In plant and animal tissues, silicon is in the form of orthosilicic acid, orthosilicic ethers, polysilicic acids, amorphous silica, crystalline impurities [Kolesnikov, 2001].

Silicon is absorbed by the lateral roots of plants in the form of a monomeric molecule of silicic acid $-\text{H}_4\text{SiO}_4$ through the active, passive and withdrawal mechanisms [Cornelis et al., 2011]. The concentration of H_4SiO_4 in the soil solution can range from 0.1 to 0.6 mM [Knight & Kinrade, 2001]. Silicic acid is adsorbed by plants from the soil solution, in which it is found in the forms of mono-silicic, oligomeric and poly-silicic acids [Iler, 1979]. Soluble silicic acid has the ability to form complexes with the organic and inorganic compounds [Williams and Crerar, 1985]. The main sources of silicic acid in the soil solution are various forms of silicon dioxide, silicates, and plant residues [Tubana & Heckman, 2015]. The amount of mono-silicic acid in the soil solution depends on many factors: solubility of the silicon-containing minerals, pH, temperature, particle size fractions, soil moisture and the organic matter content, redox potential [Savant et al., 1997]. In grassland ecosystems, the content of water-soluble silicon available to plants has a seasonal dynamics, with the highest concentrations in spring and summer, and correlates with the biological activity of the soil [Fernandes & Macias, 1987].

The Si of the solid phase of the soil and the Si of the adsorption complex can be potential reservoirs of silicon in soils. In the solid phase of the soil, silicon is part of weakly crystalline, micro-crystalline, amorphous and crystalline forms. The largest amount of Si is concentrated in the crystalline forms of primary and secondary silicates, silica. The amorphous fraction of the solid fraction Si has a biogenic and litho/pedogenic origin [Matichencov & Bocharnikova, 2001]. The total content of amorphous silica in soils ranges from 1–30 mg g⁻¹ [Jones, 1969; Drees et al., 1989]. Silicon of the adsorbed and liquid phases consists of H_4SiO_4 , polysilicic acid, dissolved forms of organic and inorganic silicon compounds. Absorption of silicic acids in the soil occurs on clay minerals, iron and aluminum oxides [Hansen et al., 1994; Dietzel, 2002].

The basis of the mineralogical composition of the studied soils (dark gray podzolic soils and chernozems podzolic) are the silicon-containing minerals of light (quartz, orthoclase, microcline, plagioclase, mica, glauconite, chalcedony) and heavy (zircon, sphe, tuna, pomegranate), epidote, actinolite, augite, kaolinite, montmorillonite, hydromica, chlorite, nontronite) granulometric fractions [Lysenko, 1978]. These minerals are the main source of silicon in the liquid, adsorbed and solid phases in the soils of the Khmelnytsky region. As a result of natural weathering of minerals, silicon of plagioclase, orthoclase and microcline, hornblende enters the soil solution at a rate of $10^{-20.5}$ to $10^{-15.2}$ mol cm⁻²s⁻¹ [White, 1995]. In heavily weathered soils and the soils that are intensively used in agriculture, the time of release of silicon into the soil solution is longer [Tubana, Heckman, 2015]. As a result, the silicon available to plants is temporarily removed from the cycle and the plants need additional application of silicon fertilizers during this period. Most soils in Ukraine have a satisfactory supply of available silicon. However, peatlands, alluvial-sod, sod-lithogenic, sod-podzolic and light gray soils of long-term agricultural use, as well as all organogenic and cation-poor soils have a deficiency of silicon available to plants [Foy, 1992; Snyder et al., 1986; Dantoff et al., 1997]. Dark gray podzolized soils and chernozems podzolized are soils with good and high supply of exchangeable cations and, accordingly, the buffering capacity. The silicon of the soil-absorbing complex of these soils goes into the soil solution and replaces the silicon of the soil carried out by plants. At the same time, during the warm period of the year, against the background of decreasing moisture content available to plants, the concentration of orthosilicic acid increases, which leads to the polycondensation reactions of silanol groups with the formation of the siloxane-type bond in polysilicic acids, which form macromolecules of colloidal size. This process is enhanced by the presence of the hydrocarbonate ions in soils [Brinker & Scherer, 1990]. In the Forest-Steppe of Ukraine, the groundwater of the left banks of rivers and floodplain terraces often contain hydrocarbons, which contribute to the processes of polycondensation and the formation of compacted solid horizons of arable soils.

Thus, many scientists have noted the role of silicon in plant growth and development, identified the conditions and factors influencing the

presence and availability of silicon compounds in soils. Given the diversity of Ukrainian soils, their spatial and mineralogical heterogeneity and the intensity of their use, it is important in agricultural production to study different forms of silicon and clarify their relationship with the adsorption complex and soil properties, spatial location of the soil in landscape and the nature of agricultural soil use.

The main purpose of our research was to determine the content of silicon compounds with different mobility in the arable layer of phaozems and chernozems podzolized of the Khmelnytsky region, to assess the spatial variation of these parameters, as well as to identify the relationship between the silicon compounds in soils with particle size distribution and calcium and magnesium exchange cations.

MATERIAL AND METHODS

Study Area

The study area is located nearby the towns of Khrolyn (50.157127N, 27.250299E) and Hrytsiv (49.970262N, 27.219525E) Shepetivka district, Khmelnytsky region. The research sites were operated by LLC “LotivkaElit”. The area is located in the Forest Steppe zone of Ukraine and has a continental climate of mild winter and warm summer. The average annual precipitation is 500–640 mm, with 70% falling from May to September. The average annual temperature is +6.8 °C and the sum of available accumulated temperature ($\geq 10^\circ\text{C}$) is 2455°C.

The soil types were classified as Phaozems and Chernozems according to the FAO soil classification (Dark forest soil and Podzolized chernozem – in Ukrainian Soil Classification). These soils were formed during the Quaternary period on losses under the influence of forest and grass vegetation. Farmland is a main type of a land use in this area. The crops grown on all plots included: corn for grain, winter wheat, spring barley, sugar beet, sunflower, soybean.

Sampling and Measurement

Both Phaozems and Chernozems are characterized by a good level of soil fertility parameters. The humus content in the upper soil layer reaches 3.0–3.5%. The content of available phosphorus

compounds – average and high, of available potassium compounds – high. The natural development of podzolic processes and agricultural land use with high amounts of nitrogen fertilizers led to a weakly acidic, and in some places to a moderately acidic pH of the soil solution. A random sample-method was used for taking composite soil samples from the depth of 0–25 cm by a sampling auger (length is 25 cm). A total of 60 soil samples from the cultivated fields were collected during this study: 30 samples – from Khrolyn (site numbers 1–4) and 30 samples – from Hrytsiv (site numbers 5–8) areas (Fig. 1; Table 1).

The soil samples were taken according to ISO 18400–102: 2017. Preparation for chemical analysis was carried out in accordance with DSTU ISO 11464–2007. The following parameters were determined in the soil samples: particle size distribution and content of fractions of particle size elements of different sizes according to DSTU 4730: 2007; pH of salt extract according to DSTU ISO 10390:2007; humus content (SOM) according to DSTU 4289: 2004; mobile

compounds of phosphorus and potassium according to DSTU; the content of exchangeable cations of calcium and magnesium by extraction with 1.0 M solution of KCl. The silicon compounds in soils were determined by using the method of Mullen and Riley with extraction of silicon by V.V. Matichenkov [Titova et al., 2011]. This method allows determining the content of mono-silicic acids in the soil. In order to determine the different degree of availability of silicon compounds 2 types of extraction solutions were used: readily available (soluble) silicon was determined by extraction with 0.01 M CaCl₂ solution, hardly available (extractable) silicon was determined by extraction with 0.1 M HCl, in the ratio soil: solution 1:10, time interaction of soils with extraction solutions was 1 hour.

Statistical Analyses

IBM SPSS Statistics for Windows v. 20.0 (© SPSS, Chicago, Illinois) was used for all of the statistical analyses. The t-test was performed

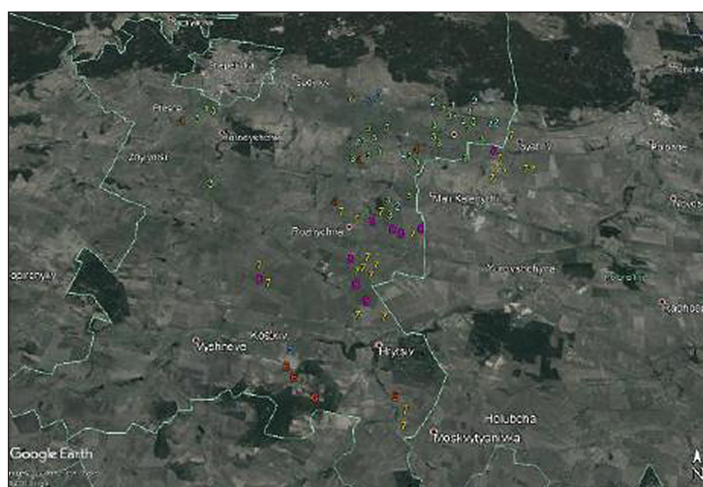


Figure 1. Location of the study area, distribution of sample sites

Table 1. Soil sampling per towns (sites)

PC	Khrolyn				Hrytsiv				
	PU	MS	SN	NS	PU	MS	SN	NS	
< 25.0	Level plains	Podzolized chernozem	1	3	Level plains	Podzolized chernozem	5	3	
25.0–30.0	Level plains	Podzolized chernozem	2	4	Gently slopes	Phaozem	6	8	
30.0–35.0	Gently slopes	Podzolized chernozem	3	13	Gently slopes	Phaozem	7	15	
35.0–40.0	Gently slopes	Podzolized chernozem	4	10	Level plains	Podzolized chernozem	8	4	
Total				30	Total				30

Notes: PC – Physical clay ($\Sigma < 0.01\text{mm dia}$) content, %; PU – Physiographic units; MS – Major soil; SN – Site number; NS – Number of samples

to search for the statistical differences between values. A Pearson's correlation coefficient was used to analyze the relationship between the dependent and independent variables.

RESULTS AND DISCUSSION

With long-term agricultural use of soils, a significant amount of available Si is taken up by plant biomass, which leads to a significant decrease in the content of silicon forms available to plants [Meunier et al., 2008; Dantoff et al., 1997]. The studies conducted in the United States showed that the removal of silicon by sugar cane and rice is about 300 and 500 kg/ha per year, respectively. U.S. natural grassland ecosystems remove only 22–67 kg/ha of silicon per year [Meyer & Keeping, 2001; Blecker et al., 2006; Makabe et al., 2009]. Overall, between 210 and 224 million tons of Si are taken up annually by agricultural plants [Bazilevich, 1993; Savant, 1997; Titova et al., 2011]. At the same time, there is almost no information in the scientific literature concerning the spatial heterogeneity of silicon compounds, their relationship to the landscape, particle size distribution, composition of exchange cations, nutrients, crop yields, etc. In accordance with the set goal, the selected soil samples were divided into four groups according to their content of physical clay ($\Sigma < 0.01$ mm): 1. <25.0%; 2. 25.0–30.0%; 3. 30.0–35.0%; 4. 35.0–40.0% (Table 1). The largest number of spatially selected samples (42 samples, 70%) was characterized by the medium loam texture. Site numbers 1–2 and 5–6 had a weakly acidic pH medium (pH 5.1–5.5), very low (1.7%) and low (2.4–3.0%) humus content, medium exchangeable calcium content (1120–1540 mg·kg⁻¹),

average and medium content of exchangeable magnesium (130–170 mg·kg⁻¹) (Tables 2–3). The average values of extractable silicon content were 366–849 mg·kg⁻¹ in terms of SiO₂. That is, the content of these silicon compounds in soils was 2.4–4.2 times lower than the content of exchangeable calcium. In the soils of the Hrytsiv array there are tendencies of expansion of the Ca/SiO₂ ratio with an increase in the content of physical clay in the soils. In the soils of the Khrolyn array there is no regularity in the change of this ratio. The soils of the Shepetivka district of the Khmelnytsky region had mainly low-deficit silicon balance, both soluble and hard extractable forms.

Relationship between soil silicon and soil parameters

The significant positive and negative correlation (r , $P < 0.05$) was found between soluble SiO₂ and soil particles > 0.05 mm dia from 1, 2, 4–6, 8 sites (Table 4). The correlation coefficient (r) was: -0.59, 0.61, 0.65, -0.57, -0.92 and -0.82 respectively. A significant relationship was also found between soluble SiO₂ and: – soil particles < 0.01 mm dia for the sites: 2 (-0.63), 4 (0.71); – soil particles < 0.001 mm dia for the site: 4 (0.89); – pH_{KCl} for the sites: 4 (0.97), 5 (0.95); – SOM for the site 5 (1.00); – P₂O₅ for the sites: 1 (0.71), 2 (0.64), 4 (0.99); – K₂O for the sites: 1 (0.99), 2 (0.80), 5 (0.87); – Mg for the sites: 1 (-0.95), 4 (0.97), 5 (0.99). Almost no correlation was found between soluble SiO₂ and exchangeable Ca and Σ Ca+Mg. For the extractable SiO₂, the significant relationship was found with: – all soil particles for the site 4 (-0.83, -0.87, -0.98); – pH_{KCl} for the sites: 4 (1.00), 5 (0.95), 8 (0.86); – SOM for the sites 1 (0.87) and 5 (1.00); – P₂O₅

Table 2. Results of analyses of the soil samples from the study area

Site number	Content of soil particle fractions, %						pH (I:2.5 KCl)		SOM, %		Σ Ca+Mg, mmol 100 g ⁻¹	
	< 0.01 mm dia		< 0.005 mm dia		< 0.001 mm dia		mean	SD	mean	SD	mean	SD
	mean	SD	mean	SD	mean	SD						
1	22.3	14	17.7	16	14.1	35	5.5	11	1.7	12	7.0	17
2	27.4	4	23.3	8	17.1	12	5.3	19	3.0	50	10.4	35
3	31.9	3	27.0	4	19.5	17	5.2	10	2.4	25	12.4	13
4	35.0	1	32.0	22	25.8	26	5.5	11	2.0	35	12.0	11
5	20.6	9	19.0	21	14.0	31	5.6	5	2.5	32	7.9	29
6	27.1	6	23.3	3	18.6	12	5.1	12	2.4	17	8.8	15
7	32.9	5	28.2	5	20.2	8	5.6	7	3.0	17	13.6	7
8	35.8	2	27.6	12.7	20.0	10	5.7	9	3.1	17	14.7	12

Note: SD – standard deviation, %

Table 3. Results of analyses of the soil samples from the study area

Site number	Exchangeable Ca, mg kg ⁻¹		Exchangeable Mg, mg kg ⁻¹		Soluble SiO ₂ , mg kg ⁻¹		Extractable SiO ₂ , mg kg ⁻¹		Exchangeable Ca/ Extractable SiO ₂
	mean	SD	mean	SD	mean	SD	mean	SD	
1	1120	17	170	36	127	76	465	30	2.4
2	1800	39	165	31	112	36	583	41	3.1
3	2200	13	170	25	131	44	692	21	3.2
4	2130	11	165	10	143	46	506	24	4.2
5	1370	31	130	27	125	6	366	76	3.7
6	1540	16	135	13	120	75	514	41	3.0
7	2380	8	205	23	117	48	670	25	3.6
8	2580	12	213	35	119	33	849	46	3.0

Note: SD – standard deviation, %

for the sites: 2 (0.82), 4 (-0.97), 6 (0.87); – K₂O for the sites: 1 (-0.95), 2 (0.76), 5 (0.85); – Mg for the sites: 1 (0.99), 5 (0.99); – Ca/SiO₂ for the sites: 1 (-0.78), 5 (-0.72); – \sum Ca+Mg for the sites: 1 (-0.64), 4 (-0.94); 6 (-0.99). There were almost not found correlation between extractable SiO₂ and exchangeable Ca.

The data obtained indicate a certain pattern of changes in the SiO₂ content from the spatial position of the experimental site and soil parameters. The highest content of soluble SiO₂ was observed at site number 4 (143 mg·kg⁻¹) (Table 3). Geomorphologically, this area is the lower part of the steep slope of arable land, which accordingly affected the migration of soluble SiO₂ in this area. The highest content of extractable SiO₂ was observed at site 8, the study areas of which were located mainly at the beginning of the ravines, which also indicates the influence of the migration processes on the accumulation of the extractable SiO₂ in these micro-sites. The content of soluble SiO₂ was most correlated with the fraction

of sand, pH_{KCl}, K₂O and Mg and almost did not depend on the content of SOM, Ca and \sum Ca + Mg (Table 4). The largest number of significant correlations of extractable SiO₂ was found with pH_{KCl}, P₂O₅, K₂O and Mg (Table 5).

Relationship between soil silicon and crop yields

As noted above, silicon is a constitutional element of plants, most of which respond well to the application of silicon fertilizer [Voronkov & Kuznetsov, 1984; Onodera, 1917; Miyake and Adachi, 1922; Yoshida et al., 1959; Anderson, 1991; Long et al., 2018, Raleigh, 1939; Lipman, 1938; Sommer, 1926; Conner, 1921]. Our studies showed the best correlation between extractable SiO₂ with spring barley yield ($r = 0.651$; $P = 0.041$) and soluble SiO₂ with corn for grain yield ($r = 0.514$; $P = 0.128$) (Table 6). Other crops did not have a significant correlation with the content of SiO₂ in soils.

Table 4. Pearson correlation (r) between the soluble SiO₂ (mg·kg⁻¹) and the soil parameters of sites 1–8

Soil parameters	Sites							
	1	2	3	4	5	6	7	8
> 0.05 mm dia	-0.59	0.61	0.11	0.65	-0.57	-0.92	0.23	-0.82
< 0.01 mm dia	-0.35	-0.63	0.24	0.71	0.28	0.45	0.19	-0.29
< 0.001 mm dia	0.03	-0.05	-0.08	0.89	-0.60	0.31	-0.05	-0.39
pH(I:2.5 KCl)	0.43	0.36	0.40	0.97	0.95	0.64	0.18	0.34
SOM, %	0.86	-0.18	-0.20	0.12	1.00	-0.22	0.02	0.06
P ₂ O ₅	0.71	0.64	0.47	0.99	0.44	0.32	0.21	0.55
K ₂ O	-0.99	0.80	0.37	-0.07	0.87	0.07	-0.01	0.46
\sum Ca+Mg, mM/100 g ⁻¹	-0.43	-0.24	-0.08	0.82	0.62	-0.62	-0.06	0.02
Ca, mg kg ⁻¹	-0.30	0.50	-0.06	-0.08	0.49	-0.11	0.07	-0.08
Mg, mg kg ⁻¹	-0.95	0.58	0.22	0.97	0.99	-0.31	0.18	0.03
Ca/SiO ₂	-0.60	0.57	-0.09	0.05	0.73	-0.12	0.10	-0.06

Table 5. Pearson correlation (r) between the extractable SiO_2 ($\text{mg}\cdot\text{kg}^{-1}$) and the soil parameters of sites 1–8

Soil parameters	Sites							
	1	2	3	4	5	6	7	8
> 0.05 mm dia	-0.36	0.71	-0.34	-0.83	0.57	-0.54	-0.13	-0.40
< 0.01 mm dia	-0.58	-0.38	0.43	-0.87	-0.27	-0.17	0.42	-0.11
< 0.001 mm dia	-0.22	-0.19	0.03	-0.98	0.61	-0.02	0.46	-0.55
pH(1:2.5 KCl)	0.64	0.40	0.52	-1.00	-0.95	0.58	0.62	0.86
SOM, %	0.87	0.12	0.09	0.15	-1.00	0.40	-0.27	0.64
P_2O_5	0.50	0.82	0.39	-0.97	-0.43	0.87	0.21	0.21
K_2O	-0.95	0.76	0.12	0.33	-0.85	-0.54	0.04	0.34
$\Sigma \text{Ca}+\text{Mg}$, $\text{mM}/100 \text{g}^{-1}$	-0.64	-0.12	0.36	-0.94	0.62	-0.99	0.69	0.09
Ca, mg kg^{-1}	-0.54	0.54	0.29	0.34	-0.48	0.60	0.38	0.63
Mg, mg kg^{-1}	-0.99	-0.06	0.36	-0.86	-0.99	-0.45	0.27	0.37
Ca/ SiO_2	-0.78	0.53	0.30	0.22	-0.72	0.53	0.40	0.71

Table 6. Pearson correlation (r) between soluble and extractable SiO_2 with crop yields

Soil parameters	Correlation	Sugar beet	Winter wheat	Sunflower	Spring barley	Corn
Soluble SiO_2 (mg kg^{-1})	r	-0.271	-0.167	0.137	-0.212	0.514
	P Value	0.162	0.623	0.480	0.556	0.128
Extractable SiO_2 (mg kg^{-1})	r	-0.355	-0.451	0.230	0.651	0.354
	P Value	0.0639	0.163	0.230	0.041	0.316
Si soluble / Si extractable	r	-0.0097	0.0710	0.083	0.183	0.020
	P Value	0.961	0.836	0.670	0.614	0.956

This fact can be explained by the significant influence of other factors on crop yields, such as: fertilizer system, soil organic matter content, available moisture content, nutrient content, etc. Thus, the spatial studies of soils are significantly influenced by the diversity of natural conditions and various agronomic measures. In determining the impact of soil silicon on crop yields, it is advisable to organize a system of scientific field experiments that would take into account geomorphological morphoscultures, lithology, different SiO_2 content in soils, fertilizer system, crop rotation, crops, etc. By organizing such studies, it is possible to determine the weight and significance of each criterion, which would depend on the content and forms of SiO_2 and predict its role in the formation of future crop yields under their normal and stressful growing conditions.

CONCLUSIONS

The spatial distribution of SiO_2 was significantly greater in the soils that formed in

footslopes. The content of an extractable silicon fraction significantly increased from a sandy loam- ($366\text{--}465 \text{mg}\cdot\text{kg}^{-1}$) to medium- ($670\text{--}697 \text{mg}\cdot\text{kg}^{-1}$) and heavy- ($506\text{--}849 \text{mg}\cdot\text{kg}^{-1}$) textured soils. The content of soluble SiO_2 was not related to soil texture. The significant positive and negative correlation (r , $P < 0,05$) was found between soluble SiO_2 and soil particles > 0.05 mm dia from: 1 (-0.59), 2 (0.61), 4 (0.65), 5 (-0.57), 6 (-0.92) and 8 (-0.82) sites. The significant relationship was between pH_{KCl} , P_2O_5 , K_2O , Mg and both forms of SiO_2 . There was almost no correlation between soluble/extractable SiO_2 and exchangeable Ca and $\Sigma \text{Ca}+\text{Mg}$. Our studies found the best correlation between extractable SiO_2 and spring barley yield ($r = 0.651$; $P = 0.041$), and soluble SiO_2 and corn for grain yield ($r = 0.514$; $P = 0.128$). No significant relationships were found for sugar beet, winter wheat, sunflower. This fact can be explained by the significant influence of other factors on crop yields, such as: fertilizing system, soil organic matter content, available moisture content, major nutrients content in soil, etc.

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