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CONTENT AND MOBILITY OF STRONTIUM IN FOREST SOILS ACCORDING TO NORTH-SOUTH TRANSECT IN POLAND

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Abstract: The investigation was carried out on forest soils collected from areas subject to variable pollution. The fraction of strontium was analyzed in soil samples from north-eastern Poland (Borki forest division), treated as a non-polluted region (natural background) and in soil samples from central (Rogów forest division) and south-western Poland (Świerklaniec forest division). The sequential extraction procedure was applied in this study to separate the fractions of strontium. Five fractions were analyzed in every genetic horizon according to the Tessier method. The concentration of strontium was also analyzed in the plants. Both results were compared in order to evaluate the mobility and bioavailability of the trace elements in the environment. The content, distribution and bioavailability of the strontium fractions were investigated with particular emphasis on the contaminated study sites. Total content of strontium in surface horizons depended on the localization. Among analysed fractions strontium, in organic soil horizons, regardless of localization, occurred predominantly in mobile fractions in all examined soils.

INTRODUCTION

Understanding of the distribution of metal fractions provides us with important data concerning not only the soil contamination but also their behavior and penetration into the biological cycle or persistence in soil. Strontium is one of the most widespread trace element able to concentrate or disperse in the soil. This divalent and alkaline element has four naturally occurring isotopes which are stable, but it can also occur as a radioactive isotope produced by fission reactions [1]. There have been many studies investigating the relationship between the radioactive ^{90}Sr isotope and its content in plants, e.g. Sysoeva *et al.* [19]. There is, however, little information on strontium uptake by different plant species and its distribution in the genetic horizons of forest soils in scientific literature. It was taken into consideration that plants can grow on soils characterized by different intensity of human activity which in turn is related to contamination with heavy metals. The content of strontium in the soil mainly depends on the parent rock but also on the individual properties of soil. The average concentration of Sr in soils is 240 ppm however it can drop below 10 ppm or excide 1000 ppm [1]. The content of strontium in magmatic rocks ranges from 2–600 to 20–600 ppm in sedimentary rocks [6]. The concentration of strontium in plants varies widely. In plants it can reach high values depending on the content of strontium in the soil. Interpretation of the soil-plant content and the phyto-accumulation factor provides data on the bioavailability of this trace element [2, 3, 20]. The study sites were chosen according to the contamination transect in Poland, which is related to industrial activity. The Puszcza Borecka area was considered as a non-contaminated region. The content of strontium in parent rock in Puszcza Borecka was thus treated as a geochemical background. Łagiewnicki forest and Rogów forest were chosen as the area with intermediate contamination, whereas Upper Silesia is representative for industrial area.

The aim of the study was to discover with which soil components strontium is mostly bound and what is the percentage contribution of mobile fractions in comparison to total strontium content. In the study, the connection between distribution, mobility of strontium fractions and degree of anthropopressure was established. Also the purpose of this study was to determine the relation between the distribution of the bioavailable, mobile fractions of strontium in soil and the basic physico-chemical properties and accumulation of strontium in plants.

INVESTIGATION FIELDS AND METHODS

The material for analyses comprising soil and plant samples was collected from 21 points in various regions of Poland, within three sample sites: Puszcza Borecka, Rogów and Łagiewnicki forests and forest soils located in the Upper Silesia area (Figure 1). In the Borki forest division (Puszcza Borecka) fresh habitats dominated (66.5% of total area) and the least was marsh (17.7%) and humid (15.7%) habitats. In the forest stand spruce (28.1%) and pine (23.9%) species dominated. In this forest division there is the largest amount of four or more species. Diversity of forest age is not large. Mostly trees are in the age from 41 to 50 years. Deciduous and semi-deciduous forest with oak, hornbeam, maple

Fig. 1. Location of thestudy sites

and pine occurred in the Rogów forest division. Coniferous species of trees dominated in this forest division (83% of total area). The average age of trees is 52 years. In the Świerklaniec forest division the age of forest stands is approximately 56 years. Pine and larch (66%) and spruce are dominating.

Strontium fractions were analyzed according to the Tessier method. This method was chosen because of its common application and the possibility of rigorous compliance of the test conditions [5, 12, 13, 14, 15]. Following the Tessier *et al.* procedure five main fractions of strontium were identified, i.e. water soluble plus exchangeable (SE-F1), bound to carbonate or weakly specifically adsorbed (WSE-F2), bound to Fe or Mn oxides (OX-F3), bound to organic matter (OM-F4) and residual fraction (R-F5). Mobile fractions were: F1 and F2 [3, 4, 18, 20]. The main physico-chemical properties were also analyzed. Profiles (two meters depth) were made with a traditional method – they were dug up with a shovel. Consequently, samples were collected from each of the genetic horizon. The soil samples were air dried, crushed and sieved through a 1 mm mesh prior to analysis. The basic soil properties determined included: hydrogen ion concentration (pH-meter), particle size distribution (Casagrande aerometric method in Prószyński's modification) and total organic matter (TOC). Before the plant material was dried, ground and ashed, the plants were washed. The total strontium content was determined directly in the plant ash according to the ICP technique.

RESULTS AND DISCUSSION

The soils were characterized by wide range of several properties: pH (from acidic to weakly alkaline), organic matter content (0.05 to 32.6%) and particle size distribution (mostly sandy soils but also silty loams and dusts) (Table 1).

An increase of pH was observed together with the depth in soil profiles. The distribution of the total organic carbon content showed variability between the organic and mineral horizons and the highest values were characteristic of the organic and accumulative horizons. A wide range of total strontium concentration was also found (Table 1). The range of total metal concentrations varied from the background values in Puszcza Borecka to the levels recognized as contamination in the Upper Silesia region. The soils tested were Luvisols and Rusty soils.

It has been suggested that the mobility and bioavailability of metals decrease approximately in order of the extraction sequence [2, 20]. In this research, strontium was classified into five fractions. The bio-available fractions included: the water soluble and exchangeable fractions (F1) extracted with 1M $MgCl_2$ and the carbonate fraction (F2) extracted with 1M NaOAc solution, respectively [20].

Exchangeable and carbonate fractions may indicate the form in which strontium is most available for plant uptake and metals retained in residual fraction are expected to be immobile in soil [9, 11, 18]. In the surface organic genetic horizons, regardless of the soil types, strontium occurred predominantly in bioavailable fractions. In these fractions, the strontium content was about 29–71% with respect to other fractions. A similar trend was observed in soils from the Łagiewnicki forest, Rogów and the Upper Silesia region. Different results were obtained by Madeyski *et al.* who analysed fractions of Zn, Cu, Pb and Ni in bottom sediments, according to Tessier method. Heavy metals in the smallest amount occurred in most available fractions (F1+F2) [11, 20]. In accumulative genetic

Table 1. Basic properties of the soil samples in typical profiles mean values in characteristic horizons

Genetic Horizon	**Soil Properties**			
	Total Organic Carbon (%)	**pH KCL**	**pH H_2O**	**Silt and Clay content (%)**
PUSZCZA BORECKA				
Rusty Soils				
O	20.86	3.5	4.1	–
A	0,36	3.9	4.5	24
Abv	0.12	3.9	4.5	29
Bv	0.08	3.6	4.9	24
BvC	0.04	3.7	5.2	18
C	0.05	3.9	5.3	13
Luvisols				
O	24.17	3.7	4.6	–
A	0.71	3.4	4.9	59
Eet	0.29	3.2	4.9	60
Bt	0.28	3.4	4.9	74
C	0.19	4.4	6.0	76
ROGÓW, ŁAGIEWNICKI FOREST				
Rusty Soils				
O	32.66	4.5	5.0	–
A	1.07	3.7	4.3	12
Abv	0.63	4.3	4.9	6
Bv	0.01	4.4	4.9	5
BvC	0.01	4.2	4.8	19
C	0.01	4.1	4.8	13
Luvisols				
O	25.04	3.8	4.6	–
A	0.53	4.0	4.6	13
Eet	0.25	4.2	4.5	21
Bt	0.13	3.8	4.2	25
C	0.00	4.0	4.4	6
UPPER SILESIA				
Rusty Soils				
O	22.42	3.6	4.8	–
A	1.77	3.3	3.9	6
Abv	0.84	4.0	4.4	4
Bv	0.36	4.4	4.5	3
BvC	0.01	4.4	4.5	1
C	0.01	4.5	4.9	4
Luvisols				
O	30.99	3.4	4.2	–
A	2.15	4.2	4.9	5
Eet	0.54	4.2	4.7	6
Bt	0.39	4.3	4.7	10
C	0.03	4.5	5.6	5

Table 2. Mean content (± SD) of strontium fractions in investigated soils (n=7)

Genetic horizon	**Fraction of strontium (mg.kg^{-1} s.m)**					
	F1	**F2**	**F3**	**F4**	**F5**	**Σ(F1-F5)**
PUSZCZA BORECKA						
Rusty soils						
O	7.47±0.01	1.44±0.01	2.58±0.05	0.65±0.06	0.05±0.05	**12.19**±0.18
A	0.37±0.07	0.06±0.01	0.10±0.23	0.14±0.20	3.30±0.40	**3.97**±0.91
Abv	0.28±0.01	0.09±1.16	1.15±0.98	0.12±0.76	10.42±0.36	**12.06**±3.27
Bv	0.17±0.65	0.10±0.02	0.17±0.12	0.11±0.12	7.01±0.01	**7.56**±0.92
BvC	0.14±1.20	0.07±0.96	0.11±0.02	0.08±0.04	7.17±0.96	**7.57**±3.18
C	0.08±0.05	0.05±0.29	0.08±0.03	0.11±0.05	5.07±0.44	**5.39**±0.86
Luvisols						
O	1.45±0.77	2.06±0.30	2.95±0.02	1.34±0.01	10.05±0.97	**17.85**±2.07
A	0.57±0.99	0.13±0.50	0.18±0.01	0.13±0.45	7.82±0.01	**8.83**±1.96
Eet	0.20±0.76	0.11±0.17	0.31±0.01	0.10±0.02	8.47±0.21	**9.19**±1.17
Bt	0.29±1.16	0.16±0.06	0.34±0.27	0.11±0.85	6.59±0.01	**7.49**±2.35
C	0.19±0.03	0.10±0.21	0.22±0.42	0.13±0.51	4.62±1.12	**5.26**±2.29
ROGÓW, ŁAGIEWNICKI FOREST						
Rusty soils						
O	16.05±0.62	4.66±0.07	6.93±0.38	1.86±0.07	0.01±0.28	**29.51±1.42**
A	0.44±0.05	0.14±0.19	0.32±0.02	0.23±0.16	13.22±0.15	**14.35±0.57**
Abv	0.26±0.30	0.06±0.01	0.14±0.05	0.10±0.06	15.68±0.11	**16.24±0.53**
Bv	0.19±0.13	0.06±0.02	0.17±0.03	0.09±0.01	17.78±0.06	**18.29±0.25**
BvC	0.13±0.04	0.03±0.12	0.10±0.01	0.09±0.85	9.85±0.99	**10.20±2.01**
C	0.23±0.06	0.05±0.11	0.09±0.01	0.12±0.41	13.49±0.20	**13.98±0.79**
Luvisols						
O	9.57±0.11	1.85±0.04	2.34±0.50	0.75±0.02	0.01±0.05	**14.52±0.72**
A	0.19±0.24	0.07±0.45	0.16±0.09	0.17±0.01	13.96±0.02	**14.55±0.81**
Eet	0.15±0.01	0.06±0.20	0.20±0.03	0.10±0.04	20.11±0.01	**20.62±0.29**
Bt	0.59±0.21	0.12±0.09	0.17±0.88	0.08±0.34	17.94±0.30	**18.90±1.82**
C	0.22±0.78	0.03±0.05	0.03±0.05	0.04±0.23	2.79±0.35	**3.11±1.46**
UPPER SILESIA						
Rusty soils						
O	12.52±0.01	1.80±0.24	3.20±0.66	0.35±1.74	3.20±1.08	**21.07±3.73**
A	1.56±0.02	0.26±0.09	0.41±0.24	0.31±0.16	0.29±0.17	**2.83±0.68**
Abv	0.85±0.01	0.16±0.02	0.30±0.13	0.19±0.50	0.28±0.41	**1.78±1.07**
Bv	1.74±0.06	7.66±0.03	1.49±0.25	0.56±0.27	1.40±0.25	**12.85±0.86**
BvC	1.34±0.04	7.61±0.02	0.89±0.07	0.33±0.15	0.82±0.18	**10.99±0.46**
C	1.56±0.25	9.90±0.21	1.05±0.02	0.35±0.01	0.99±0.01	**13.85±0.50**
Luvisols						
O	12.71±0.01	2.22±0.85	6.49±0.01	2.43±0.07	0.01±0.03	**23.86±0.97**
A	2.35±0.20	0.35±0.07	0.57±0.65	0.37±0.21	5.14±0.04	**8.78±1.17**
Eet	1.99±0.01	0.22±0.43	0.31±0.26	0.27±0.20	0.33±0.06	**3.12±0.96**
Bt	3.69±0.05	0.29±0.05	0.32±0.27	0.29±0.10	30.00±0.02	**34.59±0.49**
C	7.40±0.99	13.71±0.11	3.50±0.02	1.83±0.01	16.60±0.09	**43.04±1.22**

horizons, strontium occurred mainly in residual fraction and the sum of bioavailable fractions did not exceed 11%. Strontium was found in the residual fraction in the mineral horizons and in the parent rock. The impact of the soil type on the distribution of strontium fractions was observed in Luvisols and rusty soils (Table 1–4). Vertical movement of strontium fractions was observed in Lessivage process, which in turn had an impact on impoverishment of the total strontium content and also the fraction of strontium in Eet horizon and enrichment of Bt horizon. In rusty soils this trend was not observed. However, in rust horizons, strontium fractions connected with Fe/Mn oxides were higher than in other horizons. A similar tendency was observed for residual fraction of strontium. For better illustration of strontium distribution in the analysed soils, mean percentage concentrations of strontium fractions was presented in a graphical form (Figure 2).

The values from Puszcza Borecka (north-western Poland) were selected as the reference (baseline) values. The content of strontium in soil and its uptake in Puszcza Borecka were much lower than in the central part of Poland (Łagiewnicki forest, Rogów) and the south-eastern one (Upper Silesia). A high content of the bio-available fractions was observed in the root zone regardless of the location. This fact could have affected absorption of this element and also the content of strontium in plants [8, 17, 22]. According to Siebielec *et al.* [16], the metals in F1 are absorbed by plants in trace amounts, whereas

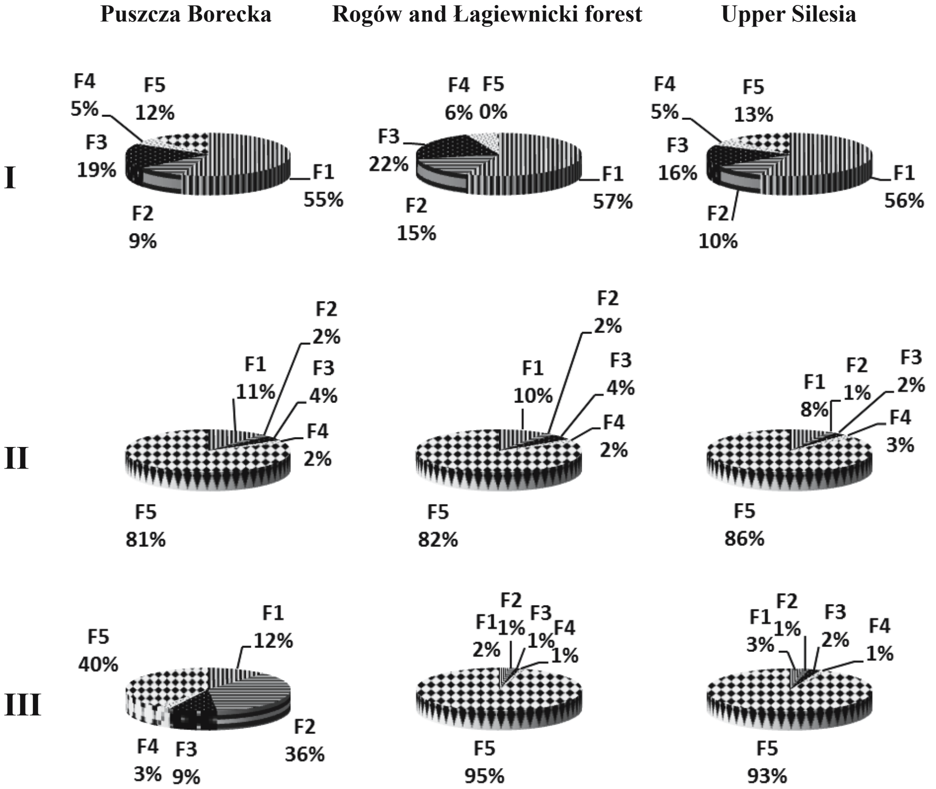

Fig. 2. Mean percentage concentrations of strontium fractions in soil diagnostic horizons I – organic horizons, II – mineral-organic horizons, III – mineral horizons

in F2 these elements are relatively well absorbed by roots but weakly transported by shoots [16, 17]. Sysoeva *et al.* [19] analyzed the forms of radiostrontium in soils; this toxic isotope also occurred mainly in the exchangeable fraction in podzolic soils. The content of strontium was determined in *Millium effusum, Impatient parviflora, Anemone nemorosa*, representing Poaceae, Balsaminaceae and Ranunculaceae. The content of strontium was determined in the above-ground parts of these plants, because although this element is not easily transported from roots to shoots and leaves, it can often occur in the above-ground parts in its highest values. The uptake of strontium mostly depends on the plant species [6, 10, 21]. A significant content of strontium in the potentially available fractions poses risk to plants, animals and humans. Strontium in soil can move into ground water posing risk to human life and health. The collected forest plants displayed a wide range of strontium concentration (Table 3). Phyto-accumulation factor is expressed as a quotient of strontium content in plant to its content in soil [10, 17]. The interpretation of the phyto-accumulation factor is as follows:

PA< 0.01 accumulation does not occur,
PA< 0.1 weak degree of accumulation,
PA< 1.0 medium degree of accumulation,
PA> 1.0 strong degree of accumulation.

Based on the calculated phyto-accumulation factors, the degree of accumulation in most plants was found to be strong (Table 2). The highest values and the phyto-accumulation factors of strontium were characteristic of *Impatient parviflora* from central and southern Poland. In the baseline area in Puszcza Borecka, the content of strontium was low and did not exceed the geochemical background for this element, whereas the phyto-accumulation factors showed low accumulation of strontium in *Millium Effussum.*

The data were treated statistically using STATISTICA 6.0 software. Correlation was assumed to be statistically significant at $p < 0.05$ and $p < 0,01$. The correlation analysis was used to identify the relationship between the soil characteristics and the strontium fractions. The correlation coefficients of the influence of the soil properties on

Table 3. Content of strontium in plants

Localization/soil type	**Plant species**	**Range**	**Mean**	**PA***
Puszcza Borecka (Luvisols)	*Millium effusum*	0.30–54.80	7.84	0.46
Puszcza Borecka (Rusty soils)		0.90–17.00	6.80	0.38
Rogów. Łagiewnicki Forest (Luvisols)	*Impatient parviflora*	14.50–20.60	16.56	4.34
	Anemone nemorosa			2.61
(Rusty soils)	*Impatient parviflora*	9.06–31.14	19.18	2.28
Upper Silesia (Luvisols)	*Impatient parviflora*	8.83–30.85	16.29	5.28
Upper Silesia (Rusty soils)		9.05–34.20	23.78	5.97

PA* Content in plant/content in soil (ΣF1+F2 in A horizon)

the distribution of the fraction of strontium confirms this relation (Table 4). Changing properties, including pH and redox conditions, may also influence Sr absorption as well as other metals [7, 12, 19]. A statistical analysis shows highly significant relations between water soluble and exchangeable fractions with clay content in soils from Puszcza Borecka, as well as with organic matter content (Łagiewnicki forest and Rogów and Upper Silesia). Carbonate and Fe/Mn oxides fractions show a significant relation with pH, which proves that pH has influence on distribution and availability of those fractions. In all study sites, the fraction connected with organic matter were strongly linked with the clay content. A similar tendency is related to residual fraction and clay content. Hypothesis on statistical significance between total content of strontium in soil profiles was confirmed only in two regions (Puszcza Borecka and Rogów) on the confidence level of 0.95.

The results of this research indicate that strontium uptake by plants depends on the soil properties, on which the plants were growing, the degree of environmental pollution (localization) and the plant species [12, 21]. The results show that the highest level of strontium occurs mostly in Upper Silesia. It was determined that there is a relation between the distribution of the bioavailable fractions of strontium in soil and the accumulation of strontium in plants. Moreover, the connection between soil type and distribution of this element was found during the research. Also a significant correlation between some soil properties and strontium fractions was calculated, which in turn proved dependence of strontium fractions in soil on soil properties. Strontium demonstrates a significant bioaccumulation affinity mostly in *Impatient parviflora* from Upper Silesia. Since there is no sufficient information and data on the content, profile distribution, different types of soils, bio-availability of this element for plants and harmful effects of high levels of stable Sr further studies ought to be continued.

Table 4. Correlation coefficient between the soil properties and the strontium fractions

Location	**Soil properties**	**Correlation coefficient**				
		F1 Water soluble and exchangeable	F2 Carbonate	F3 Fe/Mn oxides	F4 Organic	F5 Residual
Puszcza Borecka	pH	0.08	**0.74****	**0.55***	0.38	-0.29
	C (%)	-0.16	-0.12	-0.08	-0.11	**0.50***
	Clay (%)	**0.74****	-0.01	0.24	**0.50***	**0.49***
Rogów. Łagiewnicki Forest	pH	-0.03	-0.01	-0.01	-0.04	-0.16
	C (%)	**0.96****	**0.94***	**0.95****	**0.93****	-0.16
	Clay (%)	-0.28	-0.28	-0.26	-0.24	**0.35**
Upper Silesia	pH	**-0.48***	-0.43	-0.37	**-0.47***	0.16
	C (%)	**0.91****	**0.94****	**0.93****	**0.92****	-0.29
	Clay (%)	0.41	0.15	0.29	0.18	-0.16

* statistically significant at $p<0.05$
** statistically significant at $p<0,01$

CONCLUSIONS

1. Total content of strontium in surface horizons depended on the localization. The smallest amount of strontium was stated in Puszcza Borecka and the highest content of strontium was stated in Upper Silesia.
2. Among the analysed fractions strontium in organic soil horizons, regardless of localization, occurred predominantly in mobile fractions in all examined soils.
3. Studies have shown a link between distribution and mobility of strontium fractions with soil processes.

In Luvisols impoverishment of total strontium content and also mobile fractions of strontium in Eet horizon an enrichment of Bt was observed. In rust horizons strontium occurred predominantly in fractions connected with Fe/Mn oxides and was higher than in other horizons.

4. Statistical analysis has shown highly significant relations between water soluble and exchangeable fraction with clay content in soils from Puszcza Borecka, as well as with organic matter content (Łagiewnicki forest and Rogów and Upper Silesia). Carbonate and Fe/Mn oxides fractions showed a significant relation with pH.
5. Fractions connected with organic matter and residual fractions were strongly linked with clay content in all study sites.
6. The highest level of strontium in plants occurred in Upper Silesia and demonstrated a significant bioaccumulation affinity mostly in *Impatient parviflora* from this area. In the baseline in Puszcza Borecka the content of strontium did not exceed the geochemical background for this element.

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ZAWARTOŚC I MOBILNOŚĆ STRONTU W GLEBACH LEŚNYCH POLSKI W TRANSEKCIE PÓŁNOC-POŁUDNIE

Obiektem badań były gleby i rośliny pochodzące z kompleksów leśnych zlokalizowanych na terenach o zróżnicowanej antropopresji. Dlatego też obiekty badań zlokalizowano na obszarach o wzrastającym gradiencie zanieczyszczeń począwszy od Polski północnej przez centralną do południowej (Górny Śląsk). Frakcje strontu oznaczano w próbkach gleb rdzawych i płowych. Frakcje strontu w glebach oznaczono metodą sekwencyjnej ekstrakcji według Tessier'a i in. Zawartość strontu oznaczono także w wybranych gatunkach roślin. Celem badań było zidentyfikowanie form mobilnych strontu i określenie z jakimi składnikami gleby związany jest ten pierwiastek. Otrzymane wyniki wskazują na wyraźny wzrost całkowitej zawartości oraz form mobilnych strontu w poziomach powierzchniowych w zależności od lokalizacji. Ponadto stront w formach mobilnych dominował jedynie w poziomach organicznych badanych gleb.