Original Research

Influence of Physical-Chemical Characteristics of Soil on Zinc Distribution and Availability for Plants in Vertisols of Serbia

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Abstract

Sequential extraction for the determination of zinc forms in soil has been applied in order to enable clearer understanding of its mobility and availability for plants. Examinations were conducted on 20 samples of soil with different chemical and physical characteristics; plant uptake was followed on oats (*Avena sativa* L). A fractional scheme was applied with extraction of (I) water soluble and exchangeable adsorbed metals, (II) specifically adsorbed metals and metal bounded with carbonates, (III) reductant releasable Zn, which included Zn bonded to oxides not released in the previous step, and probably included Zn occluded in oxides, (IV) organically bonded, and (V) (residual fraction) metal structurally bonded in silicates. The majority of zinc is in residual fraction (V) (74.9% in field vertisols and 69% in meadow vertisols). Reductant releasable Zn occluded in oxides (III) is the second largest with higher values in meadows (22.2%) than in fields (17.5%). The content of zinc in organic matter (IV) is small (6.7%) in both types of soil. Specifically adsorbed zinc, and zinc bonded with carbonates (II) is low (0.1-3.1), while its' content in exchangeable fraction (I) is negligible and is about 0.2%. Exchangeable and specifically adsorbed zinc increased with the reduction of the pH of soil, CEC, clay and clay + silt, and with the increase of silt and sand. Zinc in the residual fraction increases with the pH of soil, clay, CEC, and clay + silt. The concentration of residual zinc was determined by mechanical fraction of clay.

Keywords: soil, solubility, plant availability, adsorption, residual zinc

Introduction

Since soil is a heterogeneous mixture of various substances, organic, mineral, mineral organic, clay, oxides of Fe, Al, Mn, many solid components, and a large number of soluble materials, the mechanisms for binding a microelement like zinc (Zn) are different and change with the type of soil; binding depends on the soil constitution and its reaction ability and reduction conditions [1-4]. Elements could form different compounds depending on many factors, such as in which components in soil they are bonded, characteristics of interacting surface layers, internal position in the crystal lattice with different bonds, etc. [5].

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Heavy metals (Zn) appear as free and complex bonded in soil solutions, nonspecifically adsorbed (exchangeable) in soil colloids, specifically as precipitates with different chemical compounds (oxides, phosphates, sulfides) and in structural lattices of primary and secondary minerals (silicates) [6].

The principal of fractional extraction of heavy metals from soil is based on the fact that metals form different bonds with solid components of soil of varied strength. These bonds could be gradually destroyed by reagents with increasing strength and specific phases of metals could be extracted. The evaluation of metal distribution in the various organic and mineral phases from soils is of great importance for the prediction of metal behavior. This includes solubility, mobility, bioavailability and thus toxicity [7, 8, 31, 33].

Heavy metals soluble in water and exchangeable adsorbed fractions in soil are extracted with neutral salts – $NaOAcNO_3$, $Ca(NO_3)_2$, NH_4OAc, $CaCl_2$, $MgCl_2$ [3, 9-12]. Heavy metals bonded with carbonates could be soluted with NaOAc – pH 5.0 [13]. For the extraction of metals bonded with organic matter, several methods have been proposed. These two steps are designed to dissolve easily reducible Fe and Mn oxides and oxidize organic matter, thereby dissolving metals bound in the "oxide" and "organic matter" soil fractions, respectively. For this purpose the following are used: hydroxylamine hydrochloride (HAC) (0.5 M) and hydrogen peroxide (H_2O_2) (8.8 M) [14]. Digestion of organic matters with 8.8 M hydrogen peroxide (acid stabilized) + extraction with of 1 M ammonium acetate (pH 2.0) was proposed by Hang et al. and Kim and McBride [12, 14]. Nevertheless, Chen et al. [15] pointed out the application of 1 M NH_2CH_3COOH – extractable metal after 30% H_2O_2 digestion.

Dissolution of a residual fraction consisting of silicate minerals, resistant sulfides, and small quantities of resistant organic materials, including alkaline fusion, or dissolution with HF (hydrofluoric) acid in combination with some stronger mineral acid (e.g. nitric or perchloric acid) which ensures full dissolution of organic matter [1, 3, 13]. To ensure complete decomposition of silicates, a large excess of fusing salt must be used, leading to high salt concentrations in the solution to be analyzed for trace metals; this can cause instability and high background readings in atomic absorption spectrophotometry. To solve this problem, Tessier et al. [13] proposed dissolution of residual fractions with a mixture of HNO_3, HF, and $HClO_4$ acids.

Different forms of Zn in soil vary significantly. Most of the metals concentrated in the residual fraction with percentages range from 60-80% for Zn [16]. The dominating chemical form for Zn was the residual (62% to 80%), with organic matter (5.9% to 22.1%) of secondary importance [17].

Heavy metals held in crystal lattices by primary and secondary minerals are not subject to remobilization under normal conditions. Similarly, the dominant proportion of Zn was also found in the residual fraction (25-81%) [12].

Contents of zinc in other fractions were low. Zn might be associated with organic matter in this uncontaminated soil containing the lowest concentration of Zn [14], and water-soluble Zn was present in small amounts less than 1% [9].

The degree of metal association with different geochemical forms strongly depends upon phyisico-chemical properties of the soils, such as pH, calcium carbonate, and organic matter content [2].

Zhang et al. [18] noticed that exchangeable zinc is dominant in soil with pH≤6.1; the organic bonded form is dominant in soil with pH in the range between 6.5 and 7.4 and bonded with Mn oxides is the main fraction where pH≥6.9.

Accessibility of zinc for plants depends on the form and its binding with soil. Zinc in water soluble, exchangeable and adsorbed fractions is easily accessible for plants. Other forms of zinc are less accessible. Stronger-bonded zinc is in minerals and this fraction is not accessible for plants. Between these two extreme cases, a large group of compounds (carbonates, oxides, organic complexes) are potentially accessible forms of zinc in soil [1, 16, 32].

Tire wear, motor oil, grease, brake emissions, and corrosion of galvanized parts may contribute to the high Zn content in roadside soils [19]. The contents of Zn at some sites can cause harmful effects on the environment [12].

The objective of the presented investigation was to determine the distribution and bioaccessibility of natural zinc in vertisol soils, utilizing its content in different fractions, as this type of soil is widespread in Serbia.

Materials and Methods

Samples were taken from vertisol soil in the Ap horizon at ten different locations in Serbia: (1) Milutovac, (2) Pristina, (3) Trnava, (4) Rekovac, (5) Vranje (Neradovac), (6) Zaječar, (7) Bela Crkva, (8) Blace, (9) Salaš, and (10) Kragujevac. Sub-samples were taken from field and meadow ecosystems at a depth of 0 to 20 cm, after which they were air-dried and crushed in a porcelain mortar up to particles 2 mm in size. A stainless steel screen was used in the preparation for characterization and Zn-fraction analyses. The remainder of the bulk sample was passed through a 2.5 – stainless steel mesh in preparation for a greenhouse experiment designed to determine plant availability of Zn in soil.

Determination of Soil Characteristics

Properties of the 10 soils are given in Table 1. Soil pH was determined in a suspension with water and 1 M KCl mixture, with the ratio of soil/solution 1:2.5 after a 0.5 – hour equilibration period; the organic content was determined using the humus method by Kotzmann [20] (Manual, 1966), the available P_2O_5 and K_2O content was determined using the Al method by Egner-Riehm [21]. CEC was determined using the method with 1 M NH_4OAc,

Table 1. Examined physical-chemical characteristics of vertisol in Serbia (mean, standard deviation, and range).

Soil characteristic	Field			Meadow		
	Mean	Range	Stand. deviation	Mean	Range	Stand. deviation
pH (H_2O)	7.1	5.8-8.1	0.9	6.9	5.6-8.1	0.9
pH (KCl)	6.0	4.6-6.9	0.9	5.8	4.7-7.0	0.9
Organic content %	3.3	2.5-4.0	0.5	3.5	2.0-5.6	1.1
P_2O_5 mg $100g^{-1}$	7.7	0.6-28.0	8.5	4.2	0.8-17.8	5.0
K_2O mg $100g^{-1}$	34.4	19.0-59.6	11.8	31.1	20.4-53.5	10.4
CEC m.e $100g^{-1}$	25.1	15.5-31.5	5.6	23.8	16.9-34.7	6.6
Sand %	29.6	21.4-36.0	4.8	32.2	22.3-50.5	9.0
Silt %	24.6	18.8-31.2	3.6	22.8	11.9-29.4	5.6
Clay %	45.8	33.5-54.4	7.2	44.9	28.9-64.3	11.1
Silt + Clay %	70.4	64.0-78.6	4.8	67.7	49.5-77.7	9.0
Zinc content total in $mg \cdot kg^{-1}$	82.7	60.0-117.0	15.3	82.1	55.0-119.0	19.0

t-test field: meadow NS – Application of the Student t-test has shown that there is no statistical significance between the examined characteristics of field and meadow soil.

pH 7, and particle size distribution was determined by a pipette method. Total Zn was determined by atomic adsorption spectrophotometry (AAS, Model Carl Zeis Jena AAS 1N) after digesting soil in acid mixtures (HF, HNO_3 and $HClO_4$).

Sequential Fractional Procedures

Zinc in different soil fractions was extracted using the procedure proposed by Tessier et al. [13]. Methods followed for the fractionation procedure are outlined below:

1. Water soluble and exchangeable metals were determined by extraction with 0.1 M $CaCl_2$ (pH 7.0). 10 g of soil was agitated in plastic pots with 100 ml of solution for 20 min, and then filtered.
2. Specifically adsorbed metals and metals bonded with carbonates were determined utilizing the extraction with 1 M NaOAc (pH 5.0). Again, 10 g of soil was added to 100 ml of solution, and agitated for 5 h at room temperature and then filtered. In this case the sums of 1) and 2) were obtained and by subtraction, fraction 2 was obtained.
3. Reductant releasable Zn occluded in oxides of Fe and Mn was determined in the following way. 2.5 mg of soil was placed in a test tube for rotation. After extraction of fractions 1 and 2, 50 ml of 0.04 M Hydroxylamine hydrochloride was added (in 25% of HOAc, pH 3). Tubes were then kept in a water bath for 6 h at 85° and stirred. After that, the total volume was set to 50 ml by adding distilled water, closed, and then agitated for 10 min., and centrifuged for 10 min. at 3,000 rotation/min. The clear solution was removed in reagent bottles, while the remains of soil were rinsed away with 20 ml of distilled water.
4. Metals bonded with organic matter were determined in the following way. 7.5 ml of 0.02 M HNO_3 and 12.5 ml of H_2O_2 pH 2.0 were added to the test tubes with the remains of soil from the previous three extractions. The tubes were kept in a water bath at 86ºC for 2 h and stirred. After cooling down, 7.5 ml of 30% H_2O_2 was added and again kept at 86ºC for 3 h. After cooling 12.5 ml of 3.2 M NH_4OAc in 20% HNO_3 was added. The final volume was set by adding distilled water and then the tubes were closed. They were then shaken for 30 min. and centrifuged for 10 min. at 3,000 rotation/min. The clear solution was transferred into reagent bottles.
5. Metals that are structurally bonded in silicates (residual fraction) were determined by calculation as the difference between the total content determined with HNO_3-HF-$HClO_4$ and the sum of the first four fractions.

Distribution of Zn in varying chemical fractions (1-4) was determined by the flame AAS method.

Vegetation Experiment

A vegetation experiment in pots was performed in order to determine the level of microelement transfer to plants and how its application influences plants and yields.

The vegetation experiment was performed in vertisol soils taken from 10 different abovementioned locations. Soil samples, taken from fields and meadows from a depth of 0-20 cm were first air dried, ground and the size of particles of soil samples used in the vegetation experiment was determined. Then the plastic containers were filled with 2 kg of soil, adding 530 $mg \cdot kg^{-1}$ NPK fertilizer 15:15:15. The following setups were formed: 1) control without microelement and 2) 8 mg per pot of Zn in the form of solute $ZnSO_4$ before seeding.

Table 2. Content of zinc in different fractions of vertisol.

Fraction location	I		II		III		IV		V		HF
	mg·kg-1	%	mg·kg-1	%	mg·kg-1	%	mg·kg-1	%	mg·kg-1	%	mg·kg-1
Field											
1	0.1	0.1	0.5	0.6	15.4	18.6	6.6	8.0	60.4	72.8	83.0
2	0.1	0.1	0.8	0.7	18.4	15.7	4.5	3.8	93.2	79.7	117.0
3	0.1	0.1	0.1	0.1	8.8	9.5	6.2	6.7	77.8	83.7	93.0
4	0.1	0.1	0.3	0.3	12.6	14.5	4.9	5.6	69.1	79.4	87.0
5	0.1	0.1	0.1	0.1	10.5	12.2	4.0	4.6	71.3	82.9	86.0
6	0.1	0.1	0.2	0.3	12.8	18.3	3.5	5.0	53.4	76.3	70.0
7	0.3	0.5	0.6	1.0	17.9	29.8	6.0	10.0	35.2	58.7	60.0
8	0.1	0.1	0.3	0.4	13.4	16.8	4.2	5.2	62.1	77.5	80.0
9	0.1	0.1	1.4	1.8	12.4	16.3	5.4	7.1	56.7	74.6	76.0
10	0.6	0.8	1.2	1.6	17.7	23.6	8.0	10.7	47.5	63.3	75.0
X±Sd	0.2±0.2	0.2	0.6±0.4	0.7	14.0±3.3	17.5	5.3±1.4	6.7	62.7±16.3	74.9	82.7
Meadow											
1	0.1	0.1	0.8	1.2	17.2	24.9	5.6	8.1	45.3	65.0	69.0
2	0.1	0.1	1.4	1.2	22.4	18.8	5.4	4.5	89.7	75.4	119.0
3	0.1	0.1	0.5	0.5	12.2	12.2	8.2	8.2	79.0	79.0	100.0
4	0.1	0.1	0.3	0.3	16.5	18.3	4.4	4.9	68.7	76.3	90.0
5	0.1	0.1	0.3	0.3	22.3	23.0	3.3	3.4	71.0	73.2	97.0
6	0.4	0.7	1.7	3.1	13.0	23.6	5.4	9.8	34.5	62.7	55.0
7	0.8	1.1	0.7	1.0	16.0	21.6	5.4	7.3	51.1	69.0	74.0
8	0.3	0.4	0.8	1.1	24.0	27.9	4.7	6.4	43.2	59.2	73.0
9	0.1	0.1	0.3	0.4	20.0	28.2	7.3	10.3	41.3	59.9	69.0
10	0.2	0.3	1.3	1.7	17.9	23.9	3.1	4.1	52.5	70.0	75.0
X±Sd	0.2±0.2	0.2	0.8±0.5	1.1	18.2±4.0	22.2	5.3±1.6	6.7	57.6±18.3	69.0	82.1
t-test	0.880NS		0.297NS		0.657NS		0.100NS		3.527		

NS – is not statistically important

t-test field: meadow NS – Application of the Student t-test has shown that there is no statistical significance between the examined fractions of field and meadow soil, exept for fraction V.

The experiment was conducted using "Slavuj" oats cultivated with 15 seeds per pot in triplicate; after two weeks the plants were thinned to ten seedlings per pot. The plants were followed 45 days in controlled laboratory conditions. Water was added to obtain optimal humidity. After 45 days the plants were dug up, rinsed with distilled water, and dried at room temperature in a dryer at t=70ºC. The dried plants were ground into a powder.

Content of Zn in oats was determined by AAS method, after treatment with HNO_3-$HClO_4$ with 30% of H_2O_2.

Statistical Analysis

Results obtained for different contents of Zn (total, accessible and different chemical fractions) in vertisol and plant material were statistically studied with Student and Pearson correlation coefficients [30].

Results and Discussion

Fraction of Zinc

Basic characteristics of examined Serbian vertisols are given in Table 1. Contents of zinc in different fractions of examined vertisols, presented in mg/kg and in % in respect to the total content, are given in Table 2.

The presented results show that the majority of zinc is in the residual fraction (V), 74.9% and 69% in field and meadow in respect to total content. Fraction (III) oxide of

Table 3. Correlation coefficient between the zinc content in different fractions and some soil characteristics for fields and meadows.

Fraction/Soil Characteristic	I	II	III	IV	V	Zn content total (HF) VI
Field						
pH (H_2O)	-0.667*	-0.813**	NS	NS	0.606*	NS
pH (KCl)	-0.672*	-0.803**	NS	NS	0.609*	NS
Humus content	NS	NS	NS	NS	NS	NS
P_2O_5	NS	NS	NS	NS	NS	NS
K_2O	NS	NS	NS	NS	NS	NS
CEC	-0.796**	NS	-0.662*	NS	0.717**	NS
Sand	0.619*	NS	NS	NS	0.805**	-0.716**
Silt %	0.642*	NS	NS	NS	NS	NS
Clay %	-0.728**	NS	NS	NS	0.803**	0.674*
Silt + Clay %	-0.619*	NS	NS	NS	0.805**	0.716**
Meadow						
pH (H_2O)	-0.795**	NS	NS	NS	NS	0.566*
pH (KCl)	-0.738**	NS	NS	NS	NS	0.599*
Humus content	NS	NS	NS	NS	NS	NS
P_2O_5	NS	NS	NS	NS	NS	NS
K_2O	NS	NS	NS	NS	0.677*	0.693*
CEC	NS	-0.593*	NS	NS	0.721**	0.667*
Sand	NS	0.598*	NS	NS	-0.615*	-0.622*
Silt %	NS	NS	NS	NS	NS	NS
Clay %	-0.574*	-0.580*	NS	NS	0.639**	0.720**
Sil + Clay %	NS	-0.598*	NS	NS	0.615*	0.622*

NS – there is no statistical significance
** statistically significant on the probability level of 0.01
* statistically significant on the probability level of 0.05

Fe and Mn is the second largest and amounts to 22.2% in meadow and 17.5% in field soil. Zinc in the organic fraction (IV) is small, 6.7% for both groups of land. Specifically adsorbed zinc bonded with carbonates (II) is low, 0.7%, while its content in the exchangeable fraction (I) is a negligible 0.2%.

Zinc Fraction According to Soil Characteristics

Relations between the Zn fraction and soil characteristics were determined using the Pearson correlation coefficient (Table 3). Analysis of the results presented in this Table show that the exchangeable fraction (I) is negatively correlated with the pH values of soil and clay content for fields and meadow. A positive correlation for fields exists with silt and sand (larger mechanic fraction of soil), pointing out weak chemical bonding with this fraction. The opposite is true for the negative correlation with clay and CEC for fields, which means stronger chemical bonding with smaller fractions of soil particles. The negative correlation with pH and CEC is explained by the larger solubility of zinc in greater acidity. In Shuman [22], exchangeable zinc was in a negative correlation with clay and CEC. A significant negative correlation between specifically adsorbed zinc (for field) and the pH value of soil indicates a tendency to increase zinc content with decreasing pH. Similar results were found in [4].

Organic bonded zinc and zinc in the oxide fraction does not have any significant correlation with the examined soil characteristics.

Zinc related to the residual fraction (V) is in positive correlation with the pH of soil, CEC, clay, and silt + clay for fields, as well as with K_2O for meadows. Residual zinc is basically determined with the clay fraction (r=0.803** and 0.639** for field and meadow, respectively). Variations of residual zinc with clay are in agreement with the findings of other authors [23-25], who showed similar correlations, indicating that the clay fraction contains plenty of residual metals.

Table 4. Correlation coefficient between zinc content in different chemical fractions in soil from fields and meadows.

Fraction	I	II	III	IV	V	Zn content total (HF) VI
Field						
I	1.00					
II	NS	1.00				
III	0.549*	NS	1.00			
IV	0.721**	NS	NS	1.00		
V	NS	NS	NS	NS	1.00	
VI	NS	NS	NS	NS	0.964**	1.00
Meadow						
I	1.00					
II	NS	1.00				
III	NS	NS	1.00			
IV	NS	NS	NS	1.00		
V	NS	NS	NS	NS	1.00	
VI	NS	NS	NS	NS	0.983**	1.00

NS – there is no statistical significance
** statistically significant on the probability level of 0.01
* statistically significant on the probability level of 0.05

Positive correlation between residual zinc and available K_2O for meadows is probably the consequence of their appearance in the same forms of binding, considering that the examined vertisols contain large amounts of clay to which K_2O is bonded in soil. Based on the presented results, it is possible to determine which zinc fractions could be used as indicators of its plant availability.

Relations among Different Fractions of Zn

Significant positive correlations are found (Table 4) for the relative content of zinc in different fractions in the vast majority of field soil (r=0.549* up to 0.983**). Correlations among exchangeable and specifically adsorbed zinc, and zinc bonded with carbonates, are not significant, showing that these two forms are almost independent. Correlations among fraction I and III (r=0.549*), and I and IV (r=0.721**) show that fractions I is related to adsorbed II and organic bonded zinc IV. Strong positive correlation was found among fractions V and HF in samples for field and meadow soil.

Plant Availability of Zinc in Soil

The correlation coefficient between zinc content in soil and its content in oat plants was also calculated (Tables 5, 6) in order to determine the chemical form of zinc responsible for its availability for plants.

The average zinc content in oat shoots from the control group amounts to 19.5 $mg\cdot kg^{-1}$ (range 15.5-23.2 $mg\cdot kg^{-1}$) for the field soil samples, and 21.7 (range 15.9-30 $mg\cdot kg^{-1}$) for meadow soil samples (Table 5). It is also concluded that the oat shoot uptake was 136.5 (95.7-173.5) $\mu g\cdot pot^{-1}$ of soil for field soil, and 165.5 (108.9-309.3) $\mu g\cdot pot^{-1}$ of soil for meadow soil. The correlation among the zinc content zinc in oat shoots and the zinc uptake by oat plants in the control group and its content in different chemical fractions was also investigated, and only fractions I (r=0.556*; r=0.770**) and I+II for zinc uptake by oat plants (r=0.508*) have significant correlations. From here, it is concluded that fractions I and II include available forms, while zinc from another fraction does not influence its content in oat shoots (Table 6).

Soil characteristics influence the zinc content in oat shoots. When all samples were included (n =20) from both

Table 5. Yield, content and uptake of Zn in oat shoots from the control group.

Ecosystems	Fields			Meadows		
	Yield	Content	Uptake	Yield	Content	Uptake
Location	$g\cdot pot^{-1}$	$mg\cdot kg^{-1}$	$\mu g\cdot pot^{-1}$	$g\cdot pot^{-1}$	$mg\cdot kg^{-1}$	$\mu g\cdot pot^{-1}$
1	7.68	16.6	127.9	7.41	20.2	149.7
2	7.48	20.5	153.3	7.10	21.4	151.9
3	5.86	23.2	135.9	5.53	19.7	108.9
4	6.98	22.2	154.9	7.83	21.6	169.1
5	5.43	17.6	95.7	6.38	22.7	144.8
6	7.93	16.2	128.5	7.88	22.1	173.9
7	7.48	15.5	115.9	10.31	30.0	309.3
8	6.60	21.2	139.9	7.21	19.9	143.5
9	6.75	20.6	139.9	7.90	15.9	125.6
10	7.96	21.8	173.5	8.21	21.7	178.2
X±Sd	7.02±0.86	19.5±2.8	136.5±21.7	7.58±1.25	21.5±3.5	165.5±54.8

Table 6. Correlation coefficient for zinc content plants and zinc content in different chemical fractions in soil.

Fraction	Content	Uptake
I	0.556*	0.770**
II	NS	NS
III	NS	NS
IV	NS	NS
V	NS	NS
I+II	NS	0.508*

NS – no statistical significance
**statistically significant on the probability level of 0.01
*statistically significant on the probability level of 0.05

Table 7. Correlation coefficient between zinc content in cultivated oat shoots and soil characteristics in vertisol in Serbia.

Soil Characteristics	Content	Uptake
pH (H_2O)	NS	-0.516*
pH (KCl)	NS	-0.443*
Humus content	0.574**	NS
P_2O_5	NS	NS
CEC	NS	NS
Clay	NS	NS
Silt	NS	NS
Silt + Clay	NS	NS

NS – no statistical significance
**statistically significant on the probability level of 0.01
*statistically significant on the probability level of 0.05

Table 8. Correlation coefficient between zinc content in cultivated oat shoots and soil characteristics in vertisol in Serbia for fields and meadows.

Soil characteristics	Field		Meadow	
	Content		Uptake	
pH (H_2O)	NS	NS	NS	NS
pH (KCl)	NS	NS	-0.590*	-0.631*
Humus content	0.916**	NS	NS	-0.542*
P_2O_5	-0.783**	NS	NS	NS
CEC	NS	NS	NS	NS
Clay	NS	NS	NS	NS
Silt	NS	NS	NS	NS
Silt + Clay	NS	NS	NS	NS

NS – no statistical significance
**statistically significant on the probability level of 0.01
* tatistically significant on the probability level of 0.05

ecosystems, a correlation (r=0.574*) was found with the humus content (Table 7). The parameter that has the most significant influence is the humus content (r=0.916**) and availability of phosphorus (r=-0.783**) from fealds soil (Table 8).

It is already known that organic matter in soil influences the distribution of microelements (Zn), and that soils with a larger content of organic matter have more available zinc [8, 26]. This means that by increasing the organic matter content, the sorption ability of vertisol for zinc increases also, which enlarges its bio availability [6].

Opposite to organic matter, available phosphorus has a negative correlation (r=-0.783**) with the zinc content in plant samples from field soil, while this effect is not present in meadow soil. This is probably caused by a small variation of available phosphorus among particular samples. Similar results were obtained by Kabata-Pendias and Pendias [2], who explained the phosphorus influence on adsorption and desorption.

Although it is often stated in literature that the pH of soil is the main determinant of metal uptake by plants [6, 27], here it is found that pH has an intermediately significant correlation (r=-0.443* and -0.516*) with the oat uptake of zinc. Radanovic et al. [28] found similar correlations for zinc in corn and *Mentha piperita* and the pH of soil. It is known that high pH has a negative influence on the availability of zinc because some ions (Ca^{+} and Mg^{2+}) and Zn^{2+} compete in plant nutrition [16].

Zinc is one of the most important essential trace elements in human nutrition. A zinc deficiency of the human body leads to several disorders, but excessive zinc intake also causes various acute and chronic adverse effects [29].

Conclusions

Using the sequential extraction method, the largest amount of zinc was determined in the residual fraction (69% in meadow soil and 74.9% in field soil).

A relatively large content of zinc in fraction III (17.5-22.2%), as well as a low content in organic matter (6.7%), is the consequence of zinc absorption by Fe and Mn oxides.

Contents of specifically bonded zinc and zinc bonded with carbonates (II) are low (0.1-3.1%) while its content in the exchangeable fraction (I) is small and about 0.2%, as indicated in Table 2.

Based on the correlation coefficients determined here, it might be concluded that the uptake of zinc by oat shoots depends mostly on easily accessible forms in soil (operational fractions I and II).

Among the studied soil characteristics, only organic matter affects the zinc content in oat shoots.

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