Distribution of soil fractions of zinc and its uptake by potatoes, maize, wheat and barley after soil amendment by sludge and inorganic Zn salt

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ABSTRACT

Zinc distribution in the main soil fractions and zinc accumulation in potatoes, maize, wheat and barley after different soil treatments (basic sludge rate, triple sludge rate, NPK, NPK + inorganic Zn) were investigated in a field experiment conducted at five localities of the Czech Republic (Červený Újezd, Hněvčeves, Humpolec, Lukavec, Suchdol) with different soil and climatic conditions. Three soil types were investigated in the experiment: clay-loamy Chernozems, loamy Luvisols, clay-loamy Luvisols and two loamy Cambisols. Sequential analyses provided an overview of soil Zn distribution in the following fractions: exchangeable, Fe-Mn oxide, organic and residual ones. The sludge and inorganic Zn addition supported Zn mobility growth and higher Zn retention in Fe-Mn oxides in all tested soils. The influence of the above-mentioned treatments on higher Zn association with soil organic compounds was not explicitly found. Potatoes, wheat and barley accumulated more Zn after its addition into the soils by sludge and inorganic salt. By contrast, Zn content in maize decreased with higher input of Zn into the soil. The highest Zn concentrations were usually observed in plants grown on both Cambisols.

Keywords: soil; zinc; sewage sludge; sequential extraction; uptake; potatoes; maize; wheat; barley; field experiment

Cleaning of wastewater produces sewage sludge. Sludge matter contains appreciable amounts of organic compounds, primary nutrients such as nitrogen, phosphorus and micronutrients. These attributes allow to use sewage sludge in agriculture (Smith 1996). However, there are other groups of compounds like toxic elements, organic pollutants and pathogenic microorganisms polluting municipal sewage sludge. Especially toxic elements can persist in the soil for an indefinite time and can be absorbed by growing plants in a wide range of quantities to affect the health of plants and/or consumers (Tlustoš et al. 2000). McBride et al. (1997) reported that 62% of zinc from heavy sludge application was found in the soil surface horizon fifteen years after sludge application.

One of the most problematic elements in sewage sludge from the aspect of soil deposition and possible toxicity to growing plants is zinc. Zinc is an essential element for plants and animals, but its high concentrations adversely affect life processes in plants, which can lead to a decrease in biomass production and deterioration of agricultural production quality (Smith 1996).

The behaviour of zinc in soil and its availability to plants depend on soil conditions, plant species, climate and agronomic practices. Zinc belongs to the most mobile trace elements that are usually retained weakly in the soils (Alloway 1990). Main factors influencing the binding capacity of soils for Zn include pH, organic matter content, clay particles and sesquioxides. Soil zinc is partitioned into different forms that have varying affinities to the above-mentioned soil constituents. Consequently, the availability of Zn soil fractions to plants is different. Zinc present in water-soluble and exchangeable forms is readily available to plants. Zinc in other forms is either potentially plant available (organically bound, bound in oxides and sulphides) or plant unavailable as a residual form (Adriano 2001). Zinc reacts to changes in soil pH sensitively. The amount of available zinc in soil solution increases with a decrease of pH value. The adsorption by clay particles controls the circulation of zinc in soil in acid conditions. Chemisorption on sesquioxides and bonds on organic ligands dominate in alkaline conditions (Kabata-Pendias and Kabata 1992). Soil sequential extraction allows to acquire precise information about Zn behaviour, and applicable reagent solutions of particular forms of soil zinc are obtained by this method (Němeček et al. 1998, Száková et al. 1999).

Sewage sludge treatment of soils can lead to an increase in zinc content in plant tissues (Smith 1996), and it was also confirmed by Balík et al. (1998) and Tlustoš et al. (2001).

MATERIAL AND METHODS

Distribution of Zn in the main soil fractions and its accumulation in potatoes (*Solanum tuberosum* L.), maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.) after application of

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Table 1. Main parameters of experimental soils

Locality	Červený Újezd	Hněvčeves	Humpolec	Lukavec	Suchdol
Soil type	Luvisols	Luvisols	Cambisols	Cambisols	Chernozems
Soil texture	clay-loamy	loamy	loamy	loamy	clay-loamy
pH_{KCl}	6.2	5.7	4.5	6.1	7.0
C_{ox} (%)	1.5	1.8	2.0	1.8	2.3
CEC (mval/kg)*	158	179	159	128	255
$P_{Mehlich\ II}$ (mg/kg)*	134	84	123	124	112
$K_{Mehlich\ II}$ (mg/kg)*	249	251	286	245	223
$Mg_{Mehlich\ II}$ (mg/kg)*	144	157	137	114	259
Zn_{total} (mg/kg)*	70	75	127	101	120

* dry matter

sewage sludge were investigated in a precise long-term field experiment that was conducted at five localities of the Czech Republic (Suchdol, Hněvčeves, Červený Újezd, Humpolec, Lukavec) with different soil and climatic conditions since 1996. Three soil types were investigated in the experiment: clay-loamy Chernozems, loamy Luvisols, clay-loamy Luvisols and two loamy Cambisols. Agrochemical characteristics of experimental soils are described in Table 1. Experimental plants rotated at all sites in the following sequence: 1^{st} year – potatoes (maize), 2^{nd} year – winter wheat, 3^{rd} year – spring barley. Experimental plants were grown at all sites in the following years: potatoes – 1997, 1998, 1999; winter wheat – 1998, 1999, 2000; spring barley – 1999, 2000, 2001. Silage maize (cultivars Romana, Torena, Compact) was planted instead of potatoes at Červený Újezd locality (Luvisols). The same cultivars of potatoes (Karin), of wheat (Samanta) and of barley (Akcent) were used at all sites. Each crop was grown at all localities in a separate field that was divided into five plots (60 m^2) with the following treatments: control, sludge (basic rate of sludge), sludge 3 (triple rate of sludge), NPK, and NPK + Zn.

Control plots were not treated. Fresh homogeneous anaerobically treated sewage sludge (Table 2) was applied at two different rates – basic (9.4 t/ha of dry matter) and triple (28.2 t/ha of dry matter), and it was taken from the same sewage disposal plant every year. Sludge was applied once in a three-year period only before potatoes and maize were planted. Zinc content in sewage sludge did not exceed the Zn limiting value for sewage sludge applied to agricultural soil (Ministry of the Environment 2001). The content of nitrogen in sludge matter was the crucial parameter for an amount of applied sludge. The basic rate of nitrogen in sewage sludge represents 330 kg N/ha (990 kg N/ha – triple rate of sludge) for the whole three-year cycle. This nitrogen rate added in sludge corresponded with the sum of nitrogen applied during the three-year cycle by NPK and NPK + Zn treatments. The behaviour of sludge Zn was compared with the effect of inorganic Zn treatment. Zinc [Zn $(NO_3)_2.6\ H_2O$] at an amount that agreed with the input of Zn in the triple rate of sludge was applied at NPK + Zn treatment. Zn inorganic salt was also applied only before potatoes and maize were planted. Plots of NPK and NPK + Zn treatments were treaded with nitrogen, phosphorus and potassium fertilisers.

Potato tubers, straw and grain of wheat and barley were harvested at full maturity. Samples of potato haulms were collected at time of flowering. After harvest soil and plant samples were collected, dried, treated and prepared for analyses. Plant samples were decomposed by the dry ashing procedure in a mixture of oxidising gases in APION apparatus (Miholová et al. 1993). Total Zn content in soils was determined after two-step decomposition, using APION in the first step and wet digestion by a mixture of HF + HNO_3 in the second step (Mader et al. 1998). Sequential extractions of soil and sludge samples were made according to the modified method SM&T EUR 14763 EN (Ure et al. 1993). Zn distribution in four soil fractions was tested: exchangeable (this fraction includes water-soluble, exchangeable and carbonate portions of soil Zn), bound by Fe-Mn oxides, retained by organic matter and residual fractions. Soil samples tested by sequential extraction were taken from the same plots of the particular localities where potatoes (maize), wheat and barley were planted in the years 1997, 1998 and 1999, respectively. Total contents of Zn in the soils at treatments sludge, sludge 3, NPK and NPK + Zn were calculated as the sum of mean control soil Zn contents and input of zinc into the soils at mentioned treatments. Contents of Zn in plant, soil and sludge samples were determined by AAS flame technique on Varian SpectrAA-400 apparatus. The quality of plant analyses was evaluated by reference material RM 12-02-03 Lucerne. Total content of

Table 2. Basic properties of sewage sludge

Year of application	1996/1997	1997/1998	1998/1999
Dry matter (%)	33	29	30
Zinc (mg/kg)*	1580	1363	1524
Nitrogen (%)*	3.5	3.6	3.7
Sludge addition (t/ha)*	9.4	9.3	8.8
Zn addition (kg/ha)	14.9	12.7	13.4

* dry matter

zinc in soil and sludge was controlled by RM 7003 Silty Clay Loam, and RM 12-03-12 Sludge, respectively. The experimental results were processed statistically by analysis of variance of one-way ANOVA at the 95% confidence level using Statgraphics program version 5.

RESULTS AND DISCUSSION

According to similar results of other authors (Němeček et al. 1998, Morera et al. 2001) the largest portion of soil zinc was found in residual form (80–86%). The smallest portion of soil zinc was always found in the exchangeable fraction (0.4–4.9%). The remaining portion of soil zinc was bound on Fe-Mn oxides (1.4–10.9%) and formed complexes with organic matter (3.9–16.2%). It is evident how important is the function of Fe-Mn oxides and organic matter from the aspect of the buffering capacity of soils for zinc. The comparison of soil zinc affinity to Fe-Mn oxides and organic matter in particular soils showed that the bond of zinc on organic matter markedly dominated in the case of both Cambisols at Humpolec and Lukavec localities. Furthermore, similar zinc affinity to Fe-Mn oxides and organic mater was observed on Chernozems (Suchdol), Luvisols (Hněvčeves) and Luvisols (Červený Újezd).

The sequential extraction of sewage sludge used in the experiment brought the following results: 5% exchangeable, 9% Fe-Mn oxides, 44% organic, 42% residual fraction of Zn. Because the sludge matter is really a heterogeneous material, experimental results of other authors can be very different. For example, Luo and Christie (1998) and Morera et al. (2001) reported an identically negligible amount of exchangeable zinc in sludge matter. Their published results also differed in amounts of sludge zinc retained in the remaining fractions.

The addition of basic sludge rate usually induced only small changes in exchangeable zinc content in all tested soils (Figure 1). By contrast, the application of triple sludge rate led to a considerable increase in the exchangeable zinc amount in both Cambisols. The content of exchangeable zinc did not increase so markedly in other soils. A rise of exchangeable zinc content in soils was also observed at NPK + Zn treatment, especially in both Cambisols and Luvisols (Červený Újezd). Suchdol Chernozems and Hněvčeves Luvisols also showed an increasing portion of exchangeable zinc fraction, but not so markedly. The expected higher content of exchangeable zinc was not confirmed in the soil treated with NPK + Zn compared to triple sludge rate treatment. With the exception of Hněvčeves Luvisol, the amounts of exchangeable zinc were on similar levels. These results are in contradiction with data published by Nyamangara (1998), who showed a dramatic increase of zinc concentrations in the exchangeable fraction of the soil after sludge + inorganic zinc addition in comparison with sludge amendment only.

Changes in Zn mobility in soils in the second and third year after sludge and fertiliser amendments are also illustrated in Figure 1. No significant differences in exchangeable zinc amounts were observed between the particular years of the experiment in all treatments of Hněvčeves Luvisols and Suchdol Chernozems. Whereas the remaining examined soils showed another trend of zinc mobility in the years without sludge addition. The exchangeable Zn concentration steeply rose in the second year after sludge application in Cambisols Humpolec (triple sludge rate) and Lukavec (basic sludge rate, triple sludge rate), and returned to the level close to that determined in the first year. Similar fate of zinc was observed in Červený Újezd Luvisols, but with such difference that the high degree of Zn mobility steadily remained in the third year after sludge treatment. Because it was not possible to find any larger differences between the particular years in plots treated with inorganic form of zinc, we conclude that the increase of Zn amount in the exchangeable fraction during the second and third year in soils with high sludge doses can be a consequence of elevated microbial activity which leads to a release of Zn from more easily mobilised forms of sludge matter or soil (Smith 1996). Clay-loamy Luvisols Červený Újezd and loamy Cambisols Humpolec and Lukavec appeared the most sensitive from the aspect of increasing Zn mobility after sludge application. It can be explained by their parameters: low pH (especially Humpolec), low CEC (especially Lukavec) and low content of organic matter (especially Červený Újezd).

Zinc bound on Fe-Mn oxides was another examined fraction. According to the assumption, the higher input of zinc into the soils usually caused a higher zinc amount retained by soil Fe-Mn oxides as it can be seen in Figure 2. The pattern of Zn concentrations found in this fraction in different treatments is similar to the pattern of the previous fraction, but measured concentrations were twice to three times higher. It was proved that Fe-Mn oxides substantially participated in the soil sorption capacity for sludge and inorganic zinc (Morera et al. 2001).

The last soil portion tested in relation to zinc behaviour was the organic fraction. It is obvious from the experimental results how important the role of soil organic matter is in the process of zinc retention. The influences of different treatments on development of zinc complexes with organic matter in soils were less clear compared to the results of the previous fraction (Figure 3). Immobilisation of supplied sludge and inorganic zinc by binding on soil organic compounds was determined unequivocally on Lukavec Cambisols only. Similar behaviour of added Zn was observed on Suchdol Chernozems and Červený Újezd Luvisols. The retentiveness of soil organic complexes for inorganic zinc form was established on Humpolec Cambisols. The supplement of sludge zinc caused a decrease in the amount of this element in the organic fraction of the latter soil type in the first and third year after sludge amendment. Whereas in the second year after wheat planting the zinc amount associated with soil organic component increased. The soil at Hněvčeves locality did not show any extreme zinc values in the organic fraction during the three-year cycle. Only a slight increase in zinc concentrations in the organic fraction was observed on plots with basic sludge dose and inorganic zinc treatments. Furthermore, an opposite trend

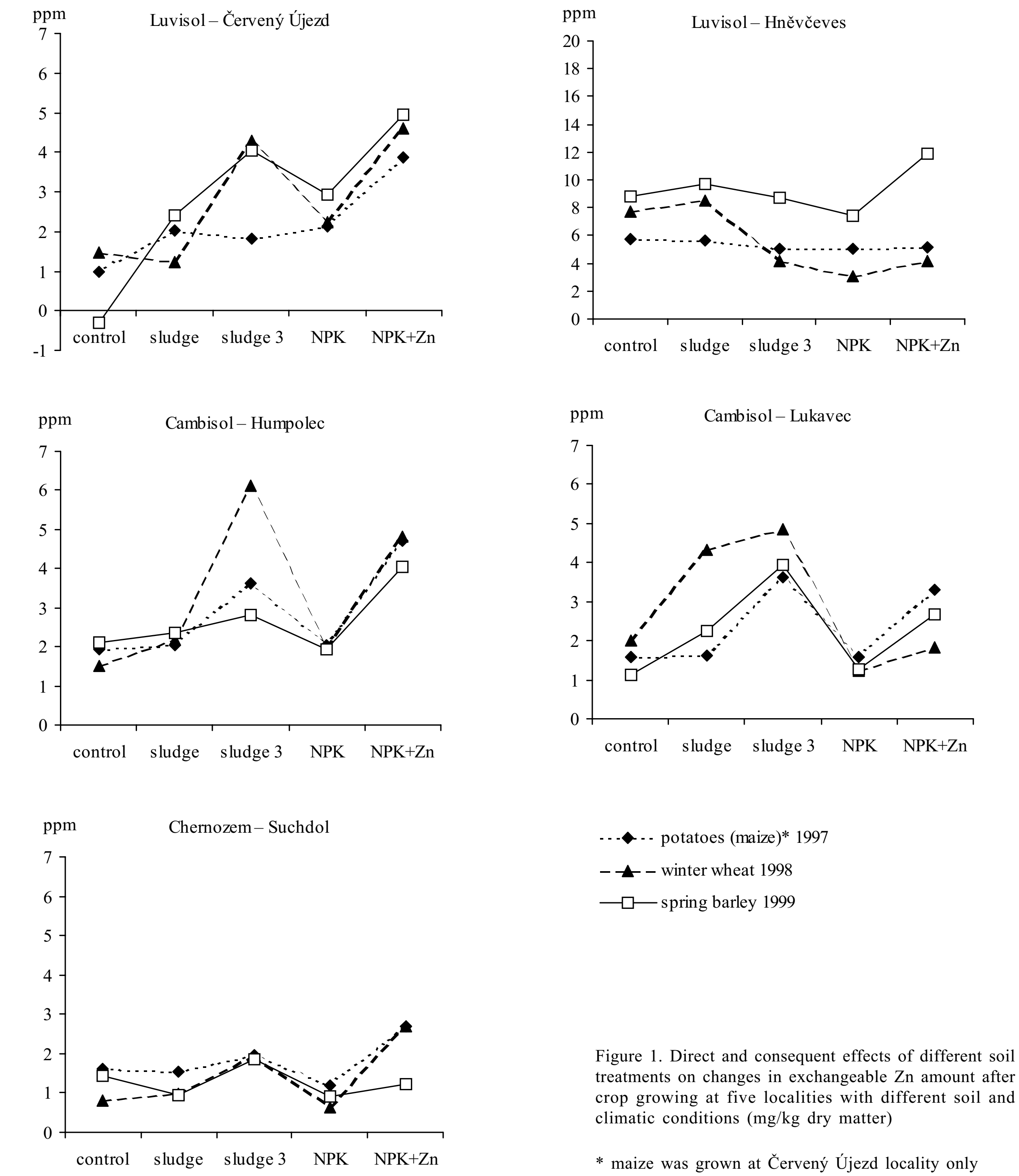


Figure 1. Direct and consequent effects of different soil treatments on changes in exchangeable Zn amount after crop growing at five localities with different soil and climatic conditions (mg/kg dry matter)

* maize was grown at Červený Újezd locality only

was ascertained on plots where the triple sludge dose was applied. It is possible to conclude from the experimental results of other authors (Berti and Jacobs 1996, Luo and Christie 1998, Nyamangara 1998, Morera et al. 2001) that the increase in zinc amount temporarily immobilised by binding on Fe-Mn oxides and organic matter of soils is affected by sludge or inorganic zinc salt addition. This expectation was confirmed only partly in our precise field experiment.

The nonliving soil organic matter is a mixture of various compounds that differ in their chemical and physical properties very much. The contributions of soil organic matter depend on the environmental conditions (climate, rock parent material, time, etc.). This variability is supported by large interactions between organic and inorganic portions of soils. Living organisms, especially soil microorganisms, fungi and also plants, interfere intensively into this world. Therefore the soil types differ crucially in the quality and quantity of soil organic matter. The soil treatment with sewage sludge, which is really a heterogeneous organic material, changes the soil properties markedly although the amount of entered

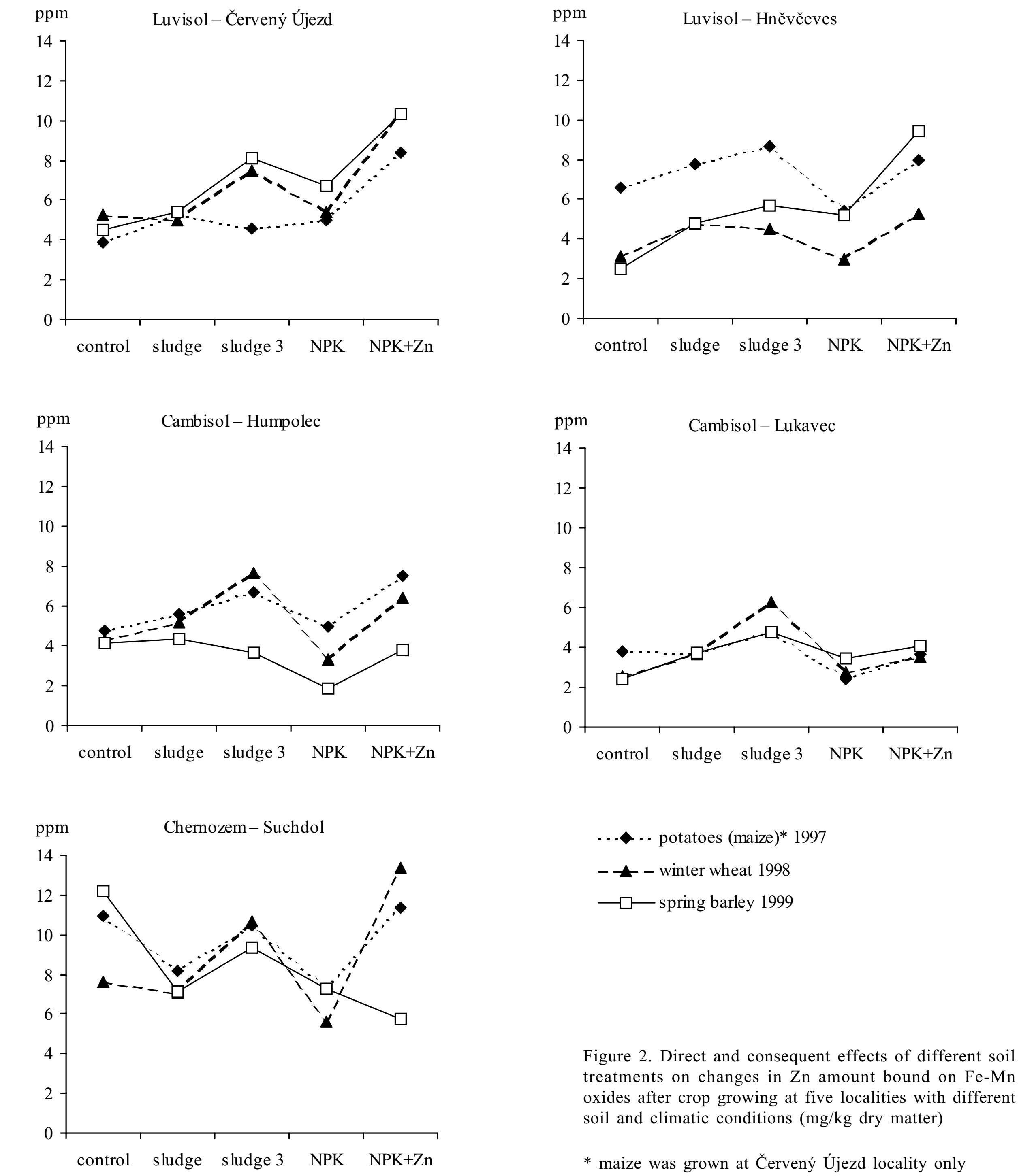


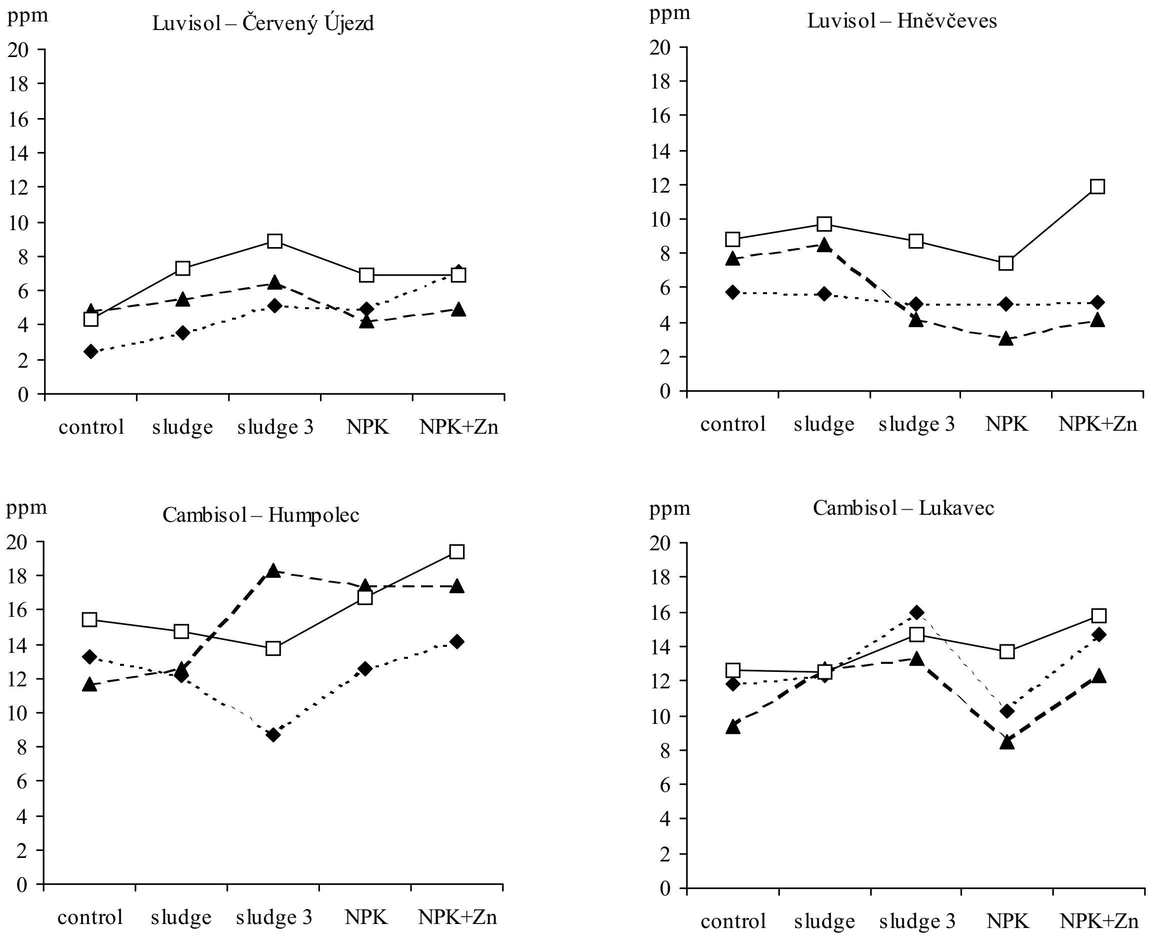
Figure 2. Direct and consequent effects of different soil treatments on changes in Zn amount bound on Fe-Mn oxides after crop growing at five localities with different soil and climatic conditions (mg/kg dry matter)

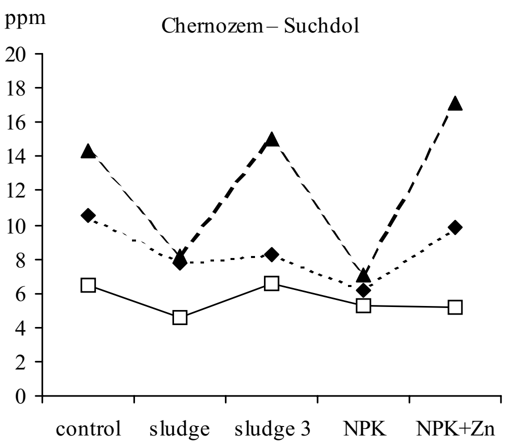
* maize was grown at Červený Újezd locality only

sludge organic matter is very small compared to total content of soil organic matter in the surface horizon (Smith 1996). These ideas can partly explain the unclear Zn behaviour in relation to the soil organic fraction found in our trial.

We can suppose from the increase in Zn concentrations in exchangeable and Fe-Mn oxides fractions in the second and/or third year after sludge application compared to the first year on both Cambisols (Humpolec, Lukavec) and Luvisols (Červený Újezd) that labile-bound zinc as a component of sludge matter was not released very much in the first year. The relatively stable Zn organic and inorganic complexes from sludge were decomposed and transformed gradually.

Potatoes and silage maize (only at Červený Újezd locality) were crops with direct sludge treatment. Potato tubers were harvested at full maturity. Samples of potato haulms were collected at the time of flowering. It is evident from Table 3 that Zn concentrations in haulms usually exceeded the Zn concentration in tubers several times. The higher input of zinc into the soil noticeably supported an increase of its accumulation in potato haulms, especially





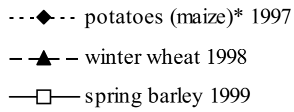


Figure 3. Direct and consequent effects of different soil treatments on changes in Zn amount bound on organic matter after crop growing at five localities with different soil and climatic conditions (mg/kg dry matter)

* maize was grown at Červený Újezd locality only

after sludge triple dose and NPK + Zn treatments. The influence of different treatments on Zn content in tubers was not so clear as in haulms. Except the Hněvčeves locality, all Zn content changes in treatments were not significant (Table 3). The three-year mean zinc contents in tubers fluctuated in the range of 10–25 mg/kg of dry matter; Beneš (1994) published these values for potatoes planted on noncontaminated soils. This author assessed the content of zinc in potato haulms too. He set up the beginning of high zinc content in haulms 50 mg/kg of dry matter. The Zn concentrations in haulms were usually below this value. The Zn concentrations in haulms exceeded slightly the latter level in the case of sludge triple rate treatment on both Cambisols Humpolec and Lukavec and markedly on NPK + Zn treatments of Hněvčeves Luvisols, Cambisols Humpolec and Lukavec. The highest concentrations in tubers and haulms were found identically on both Cambisols. The lowest Zn content in tubers and haulms was recorded on Hněvčeves Luvisols and Suchdol Chernozems, respectively. Higher mobility of soil zinc detected on both Cambisols (Figure 1) led to its elevated uptake by potato plants. Zn absorbed by

Table 3. The mean three-year zinc concentrations in potato tubers and haulms (mg/kg of dry matter) and relative changes (%) of Zn concentrations in potato tubers and haulms at different treatments compared to control treatment

Locality (Soil type)	Treatment	Tubers			Haulms		
		x	*s*	%	*x*	*s*	%
Hněvčeves (Loamy Luvisols)	control	11.7 a	4.3	–	32.4 a	5.2	–
	sludge	13.4 a	4.3	14	35.4 a	9.0	9
	sludge 3	11.9 a	1.6	1	43.9 a	11.7	35
	NPK	12.1 a	2.2	4	40.0 a	8.0	23
	NPK + Zn	15.0 a	3.8	28	65.1 b	17.6	101
Humpolec (Loamy Cambisols)	control	16.0 a	4.9	–	43.9 a	15.8	–
	sludge	17.1 a	4.3	7	48.0 a	17.3	9
	sludge 3	17.4 a	5.4	8	54.1 a	6.6	23
	NPK	15.6 a	3.5	–3	52.2 a	22.0	19
	NPK + Zn	18.3 a	3.6	14	88.7 a	41.8	102
Lukavec (Loamy Cambisols)	control	15.7 a	5.5	–	40.5 a	9.2	–
	sludge	15.0 a	2.3	–5	47.2 a	10.2	16
	sludge 3	15.6 a	5.2	–1	53.4 a	8.6	32
	NPK	16.0 a	5.4	2	40.6 a	10.2	0
	NPK + Zn	19.1 a	4.9	21	73.2 a	33.4	81
Suchdol (Clay-loamy Chernozems)	control	15.2 a	4.9	–	31.5 a	16.6	–
	sludge	13.5 a	1.9	–11	35.4 a	16.3	12
	sludge 3	16.2 a	5.0	6	39.2 a	20.3	24
	NPK	13.9 a	5.5	–9	26.7 a	9.6	–15
	NPK + Zn	15.4 a	3.7	1	38.8 a	22.3	23

a, b, c = differences between values with the same small letter are statistically insignificant at the 95% confidence level

plants was preferentially distributed into haulms, especially at the beginning of vegetation.

The results of our trial are in contrast with Mondy et al. (1984). They observed an evident increase in Zn transport into tubers by potatoes planted in field conditions (clay-loamy Cambisols) after repeated sludge applications. But the soil used in their experiment contained between 640 and 693 mg Zn/kg of dry matter. Brar et al. (2000) analysed haulms and tubers of potatoes grown in the field (Cambisols) irrigated with water contaminated by trace elements. Their experimental results showed different dynamics of zinc uptake during vegetation and efforts of plants to protect chosen parts against negative effects of higher Zn concentrations. Zn concentrations increased after 45 days of vegetation 3.5 times in haulms and 1.8 times in tubers, and after 90 days of vegetation 2.3 times in haulms and 1.2 times in tubers compared to control treatment irrigated with unpolluted water in their experiments.

Zinc content in maize biomass is described in Table 4. An obvious decrease in zinc accumulation in maize with comparable input of this element into the soil is seen there. Lower zinc contents in maize tissues after sludge application compared to the control variant are in agreement with experimental results of Tlustoš et al. (2001). They investigated the effect of sludge application on zinc uptake by maize in pot trials using Luvisols from the same site (Červený Újezd). By contrast, Balík et al. (1998), who also used these Luvisols from Červený Újezd in pot trials, reported an increase in Zn uptake by maize after sludge addition. Zn uptakes by maize in our experiment do not correspond exactly to changes in zinc content found in the exchangeable fraction after different treatments. Especially the addition of inorganic zinc salt, which caused a sharp increase in soil zinc mobility, was reflected in the lowest accumulation of Zn in maize tissues compared to other treatments.

Winter wheat was planted at all experimental sites in the second year after sewage sludge application. Because zinc in wheat plants was preferentially transported to grains and deposited there, the Zn concentrations in straw were always lower. The intervals of average zinc concentrations in wheat straw and grain were 4–38 mg/kg and 17–45 mg/kg, respectively, which corresponded with the values published by Beneš (1994). The lowest zinc concentrations in grain and straw were observed on Hněvčeves Luvisols. By contrast, wheat accumulated most Zn on Humpolec Cambisols. Zn values determined in wheat planted on Suchdol Chernozems, Červený Újezd Luvisols and Lukavec Cambisols ranged between both marginal values. As mentioned above, Humpolec Cambisols had the lowest pH out of the compared soils show-

Table 4. The mean three-year zinc concentrations in maize biomass (mg/kg of dry matter) and relative changes (%) of maize Zn concentrations at different treatments compared to control treatment

Locality (Soil type)	Treatment	x	s	%
Červený Újezd (Clay-loamy Luvisols)	control	44.0 a	18.7	–
	sludge	37.5 a	14.7	–15
	sludge 3	32.0 a	8.6	–27
	NPK	29.4 a	9.6	–33
	NPK + Zn	25.1 a	7.6	–43

a, b, c = differences between values with the same small letter are statistically insignificant at the 95% confidence level

ing a dominant effect of soil pH on high Zn availability in this soil. Hooda and Alloway (1996) also documented a positive influence of lower pH on higher Zn transfer into the wheat grain grown on sludge treated soils. The increase in soil zinc content in the exchangeable fraction at some localities in the second year after sludge application assumed higher Zn uptake by wheat in this experiment (Table 5). Winter wheat positively responded to the increased supply of available zinc in soils. Especially, the wheat plants readily accepted zinc in inorganic form compared to sludge borne zinc. The addition of sludge also supported a Zn increase in plants, especially after sludge triple rate amendment. It is important to emphasise that plants fertilised with NPK accumulated zinc at a similar amount like plants grown on sludge treated plots. The results of statistical analysis (Table 5) showed significant effects of treatments on changes in Zn content in wheat straw produced on Hněvčeves Luvisols, Cambisols Humpolec and Lukavec and in grain on Suchdol Chernozems and both Cambisols too.

Spring barley was the last tested plant in the experimental crop rotation. Barley was planted in the third year after sludge and inorganic zinc addition. Barley also

Table 5. The mean three-year zinc concentrations in grain and straw of winter wheat (mg/kg of dry matter) and relative changes (%) of Zn concentrations in grain and straw of winter wheat at different treatments compared to control treatment

Locality (Soil type)	Treatment	Grain			Straw		
		x	s	%	x	s	%
Červený Újezd (Clay-loamy Luvisols)	control	23.4 a	5.0	–	7.2 a	4.2	–
	sludge	23.3 a	5.1	0	5.8 a	4.7	–20
	sludge 3	29.4 a	7.5	26	6.5 a	4.3	–10
	NPK	26.8 a	7.0	15	6.4 a	4.2	–12
	NPK + Zn	28.2 a	3.2	21	6.8 a	3.5	–6
Hněvčeves (Loamy Luvisols)	control	17.7 a	2.0	–	5.2 ab	2.1	–
	sludge	19.0 a	2.9	7	5.0 ab	1.0	–4
	sludge 3	19.7 a	0.8	11	5.4 ab	1.5	3
	NPK	19.7 a	5.6	11	4.1 b	0.4	–22
	NPK + Zn	22.9 a	11.0	29	8.4 a	4.4	62
Humpolec (Loamy Cambisols)	control	22.5 a	2.7	–	9.7 a	2.9	–
	sludge	31.4 ab	4.9	39	14.2 a	5.7	46
	sludge 3	30.5 ab	4.0	35	7.8 a	2.1	–20
	NPK	32.9 b	2.0	46	12.7 a	3.8	31
	NPK + Zn	45.3 c	5.9	101	37.6 b	14.2	287
Lukavec (Loamy Cambisols)	control	24.1 a	4.1	–	9.0 a	1.2	–
	sludge	24.2 a	4.9	0.5	12.3 a	3.2	37
	sludge 3	27.6 ab	4.4	15	9.8 ab	2.6	9
	NPK	27.8 ab	2.3	15	9.4 ab	4.8	4
	NPK + Zn	33.6 b	7.1	40	24.7 b	17.6	175
Suchdol (Clay-loamy Chernozems)	control	19.0 a	3.1	–	7.1 a	3.0	–
	sludge	22.0 a	2.0	16	4.6 a	0.4	–36
	sludge 3	28.9 b	2.9	52	8.0 a	4.5	13
	NPK	24.9 ab	4.5	31	6.4 a	3.3	–10
	NPK + Zn	29.8 b	4.8	57	12.2 a	7.8	72

a, b, c = differences between values with the same small letter are statistically insignificant at the 95% confidence level

Table 6. The mean three-year zinc concentrations in grain and straw of spring barley (mg/kg of dry matter) and relative changes (%) of Zn concentrations in grain and straw of spring barley after different treatments compared to control treatment

Locality (Soil type)	Treatment	Grain			Straw		
		x	*s*	%	*x*	*s*	%
Červený Újezd (Clay-loamy Luvisols)	control	27.1 a	6.7	–	10.9 a	6.7	–
	sludge	26.9 a	5.9	–1	10.6 a	5.9	–3
	sludge 3	36.8 a	10.1	35	11.9 a	10.1	9
	NPK	29.6 a	13.0	9	7.0 a	13.0	–36
	NPK + Zn	35.2 a	13.9	30	7.8 a	13.9	–29
Hněvčeves (Loamy Luvisols)	control	24.9 a	5.0	–	10.6 a	5.0	–
	sludge	25.6 a	2.2	3	9.6 a	2.2	–9
	sludge 3	27.7 a	6.5	12	16.2 a	6.5	54
	NPK	20.4 a	6.0	–18	9.9 a	6.0	–6
	NPK + Zn	25.7 a	7.2	3	13.9 a	7.2	32
Humpolec (Loamy Cambisols)	control	26.4 a	4.4	–	11.7 a	4.4	–
	sludge	28.9 a	6.2	9	18.0 a	6.2	54
	sludge 3	28.0 a	7.5	6	15.8 a	7.5	35
	NPK	28.2 a	5.8	7	14.2 a	5.8	21
	NPK + Zn	37.3 a	11.1	41	14.7 a	11.1	25
Lukavec (Loamy Cambisols)	control	26.3 a	9.9	–	13.4 a	9.9	–
	sludge	27.5 a	8.6	5	15.8 a	8.6	18
	sludge 3	29.2 a	8.2	11	16.1 a	8.2	20
	NPK	26.8 a	7.5	2	12.8 a	7.5	–4
	NPK + Zn	30.3 a	10.8	15	20.5 a	10.8	54
Suchdol (Clay-loamy Chernozems)	control	24.4 a	9.5	–	11.6 a	9.5	–
	sludge	26.9 a	8.3	10	9.9 a	8.3	–14
	sludge 3	26.9 a	9.5	10	13.0 a	9.5	13
	NPK	24.0 a	4.7	–1	10.1 a	4.7	–13
	NPK + Zn	28.6 a	8.7	17	13.3 a	8.7	15

a, b, c = differences between values with the same small letter are statistically insignificant at the 95% confidence level

responded to higher Zn content in the exchangeable fraction in soils treated with sludge and inorganic zinc by the increase in its uptake (Table 6). Received zinc was preferentially deposited in grain contrary to straw similarly like in wheat. These results correspond with Balík et al. (1998) experiments. They examined the effect of sludge addition on zinc uptake by barley and its accumulation in grain and straw in pot trials. The ratio (x/y) between zinc content in grain (x) and straw (y) was lower in barley (2.19) than in wheat (2.65). Barley plants usually accumulated more zinc in grain and straw than wheat. But barley did not respond to the elevated amount of available zinc in soils so sensitively as wheat, as can be seen in Tables 5 and 6. All zinc changes in barley grain and straw after different soil amendments were statistically insignificant (Table 6). It shows decreases in Zn uptake by barley compared to wheat after all soil treatments on Humpolec Cambisols and also on Lukavec Cambisols with NPK + Zn treatment.

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ABSTRAKT

Distribuce frakcí zinku v půdě a jeho akumulace v bramborách, kukuřici, pšenici a ječmeni po přídavku čistírenských kalů a anorganické Zn soli

V dlouhodobém přesném polním pokuse založeném v pěti lokalitách ČR [Červený Újezd (jílovitohlinitá hnědozem), Hněvčeves (hlinitá luvizem), Humpolec (hlinitá kambizem), Lukavec (hlinitá kambizem), Suchdol (jílovitohlinitá černozem)] bylo sledováno působení odlišného hnojení (kal, 3× kal, NPK, NPK + anorganický Zn) na distribuci Zn mezi hlavní půdní frakce a na jeho akumulaci v bramborách, kukuřici, pšenici a ječmeni. Pomocí sekvenční analýzy byl získán přehled o zastoupení Zn mezi těmito půdními frakcemi: výměnná, Fe-Mn oxidy, organická, reziduální. Přídavek kalů a anorganického Zn do půdy obvykle zvýšil jeho podíl ve výměnné a oxidové frakci na všech lokalitách. Zvýšená retence Zn v organické frakci po půdní aplikaci kalů a anorganického Zn se jednoznačně nepotvrdila. Po ošetření půdy kaly a NPK + Zn akumulovaly brambory, pšenice, ječmen více Zn než kontrolní nehnojené varianty. Naopak v biomase kukuřice byl pozorován pokles obsahu Zn při jeho zvyšující se mobilitě v půdě. Nejvíce Zn přijímaly pokusné rostliny pěstované na kambizemích Humpolec a Lukavec ošetřených trojnásobnou dávkou kalu a anorganickým Zn. Naopak nejnižší koncentrace Zn v rostlinách byly obvykle zjištěny na černozemi Suchdol a luvizemi Hněvčeves.

Klíčová slova: půda; zinek; čistírenské kaly; sekvenční analýza; příjem; brambory; kukuřice; pšenice; ječmen; polní pokus

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