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ORIGINAL PAPER

Soil factors affecting solubility and mobility of zinc in contaminated soils

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Abstract In view of modern worldwide research carried out in the context of broadly understood soil chemistry and monitoring of the natural environment, the methods of assessing the risk of Zn contamination in soil and agricultural crops based on the analyses of Zn concentration in the soil solution have gained more recognition. Accordingly, research on the evaluation of the effects of selected soil properties on changes in solid/solution partitioning coefficient (K_d), the total concentration and activity of zinc in the soil solution was undertaken in this study. The study was based on the microplot field experiment. Investigated soil factors were as follows: soil texture, pH, organic carbon content and the degree of Zn contamination. The results indicated that zinc activity in the soil solutions was very high and comparable to the total concentration of zinc. The investigated soil properties significantly influenced the K_d, the total concentration of zinc, as well as the concentration of Zn^{2+} in the soil solution. The total concentration and activity of zinc in the soil solution increased with increasing Zn content in the soil and rising soil acidity, while they decreased with increasing the content of organic carbon and clay particles. The values of K_d increased significantly with rising soil pH and total Zn content and decreased with increasing soil organic content. Observed K_d values were significantly higher in soil with 13 % clay than in soil with 7 % clay.

Keywords Soil properties · Soil solution · Zinc activity · Zinc concentration

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Introduction

The accumulation of heavy metals in soil is of interest because of the adverse affect heavy metals may pose to food quality, soil health and the environment. At increased concentrations, Zn is toxic to soil microorganisms and plants and may adversely affect soil fertility and crop yield. Current legislative frameworks for soil pollution focus predominantly on total metal content. However, environmental risks posed by heavy metals are a function not only of their overall presence in the soil, but also of their chemical speciation (Nolan et al. 2003a). It is generally accepted that the free heavy metal ion activity (Lofts et al. 2004) or solubility (McBride et al. 1997) in soil is a much better indicator of heavy metal availability in soils than that of the total heavy metal content (McBride et al. 1997; Cancés et al. 2003). This is because heavy metals in a soil solution constitute the soil metal fraction that is most directly available for plant uptake and could potentially be leached from the soil and contaminate groundwater or surface water. Many authors have shown that the activity of metal ions in the soil solution is a key factor in determination of element bioavailability and its toxicity for various organisms (Cancés et al. 2003; Degryse et al. 2009; Parker

Table 1 Physico-chemical properties of soil

Soil particles <0.002 mm (%)	pH	SOC (g kg^{-1})	Zn (mg kg^{-1})
7.0	4.0	6.0	42.0

and Pedler 1996; Weng et al. 2001). The concentration and activity of zinc in the soil solution depends on the physical and chemical properties of the soil (Ivezić et al. 2012). Several authors have indicated the increase in the total concentration of zinc in the soil solution, under the conditions of changed soil reaction into acidic, has been connected with increased solubility and mobility of this metal (Alloway 2009; McBride et al. 1997). In soil, zinc forms complexes with organic matter quite quickly, and this has a holding back effect on the activity of Zn^{2+} in the soil solution (Cavallaro and McBride 1984; Bar-Tal et al. 1988; Fotovat et al. 1997; Hernandez-Soriano and Jimenez-Lopez 2012). The concentration of Zn^{2+} in soil solution and groundwater depended on the total content of this metal as well as the value of soil pH (Nolan et al. 2003b; Pérez-Esteban et al. 2013).

The objective of this study is to measure the solubility of Zn and its speciation in solution of contaminated soils with differentiated chemical properties. In addition, these studies will allow the assessment of the possibility of predicting the solubility and speciation of Zn in contaminated soils from simple soil properties such as soil texture, soil pH, total soil Zn content and soil organic matter content. This will also show which soil properties are most essential to control Zn speciation and mobility. The study was carried out in 2009–2011 based on the microplot field experiment located at the Experimental Station of the Faculty of Agriculture and Biology—Warsaw University of Life Sciences-SGGW, in Skierniewice (central Poland).

Materials and methods

Soil samples

The study was carried out based on the microplot field experiment located at the Experimental Station of the Faculty of Agriculture and Biology—Warsaw University of Life Sciences-SGGW, in Skierniewice (central Poland). Location of Experimental Station in Skierniewice is as follow: latitude 51°58′, longitude 20°10′, altitude 120 m. Stoneware pots (1.2 m long and 40 cm wide) filled with soil were treated as microplots. Experimental factors were as follows: (1) two soils with different clay particles (<0.002 mm) content (7 and 13 %), (2) three levels of soil pH: 4, 5 and 6, (3) three levels of soil organic carbon (SOC): 6.0, 9.0 and 12.0 g C kg^{-1} and (4) four levels of Zn content in soil Zn: (42.0 mg Zn kg^{-1} d.m. soil, 80.0 mg Zn kg^{-1} d.m. soil, 150.0 mg Zn kg^{-1} d.m. soil and 320.0 mg Zn kg^{-1} d.m. soil).

Researches collected soil from the control object (without fertilization) from the experimental field in Skierniewice. The main soil properties are shown in Table 1.

The addition of bentonite increased the content of clay particles. This provided two soils of different clay content: 7 and 13 %. These soils had differentiated pH value by the addition of CaO, differentiated organic content by the addition of brown coal and differentiated zinc content by the addition of ZnO. All soil properties were differentiated in the soil at layers of 0–30 cm.

The conducted experiment encompassed a total of 216 microplots which formed 72 combinations of investigated factors. All factors were observed in three replications in split-plot experimental design.

Analytical procedures

Soil samples for further analyses were collected from the surface soil layer of each microplot (0–30 cm deep). The soil samples were dried in the laboratory and were sieved through a sieve with a mesh of 2 mm.

Soil samples were characterized for: pH—by potentiometric method after extraction with 1 mol dm^{-3} KCl (10 g of soil was suspended in 25 mL of KCl and equilibration for 24 h) using a pH meter (apparatus: Schott) with a glass electrode; Zn—after extraction in 1 mol dm^{-3} HCl (10 g of soil was shaken with 100 mL HCl on a rotary shaker for 2 h at 120 rounds per minute) by inductively coupled plasma atomic emission spectrometry (ICP-AES) (apparatus: IRYS Advantage ThermoElementar); total organic carbon content—by dry combustion at high temperatures in a furnace with the collection and detection of evolved CO_2 with C-MAT 5500 apparatus (Tiessen and Moir 1993); content of soil particles <0.002 mm—by laser diffraction method with apparatus Mastersizer 2000 (Ryżak et al. 2007).

The soil solution was obtained by modified vacuum displacement method with the use of a vacuum pump (Dynavac OP4) according to Wolt and Graveel (1986). The total concentration of zinc in soil solution was determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) (apparatus: IRYS Advantage ThermoElementar). Calculations of the activity of free Zn^{2+} ions were performed using the software MINTEQA2 for Windows.

Statistical analysis

The results were statistically analyzed with multiple factor ANOVA, simple linear regression and multiple regression. The differences between means were detected by Tukey's

Table 2 Total concentration (Zn) and activity of free ions (Zn^{2+}) in the soil solution according as soil properties (mg L^{-1})

Form of Zn	Content of clay particles in soil		Soil reaction (pH_{KCl})			SOC content in soil (g kg^{-1})			Content of Zn in soil (mg kg^{-1})			
	7 %	13 %	pH 4	pH 5	pH 6	6.0	9.0	12.0	42.0	80.0	150.0	320.0
Zn	0.37	0.22	0.58	0.20	0.09	0.25	0.29	0.33	0.18	0.25	0.34	0.39
$LSD_{0.05}$	0.03		0.03			0.11			0.06			
Zn^{2+}	0.23	0.14	0.36	0.13	0.06	0.16	0.18	0.21	0.11	0.16	0.21	0.25
$LSD_{0.05}$	0.02		0.02			0.06			0.03			

multiple-comparison test at significance level at 0.05. Multivariate relationships were evaluated using principal component analysis (PCA). The statistical analyses were performed with Statgraphics 5.1 and Statistica 10 software.

Results and discussion

Total Zn concentration in soil solution

The average total zinc concentration in the soil solution ranged from 0.09 to 0.58 mg L^{-1} (Table 2). The values for zinc concentrations found in the present study are comparable with the results obtained by Rutkowska (1999) who determined zinc concentration levels in solutions of more than one hundred agricultural soils collected through out of Poland, which ranged from 0.20 to 0.46 mg L^{-1}. Similar concentration values were observed by Smal et al. (2000) in forest and agricultural soils, and these ranked from 0.16 to 0.46 mg L^{-1}. Lower total zinc concentrations in soil solutions were found by Sanders (1983), Curtin and Smillie (1983) as well as Gerritse et al. (1983). Stephan et al. (2008) in 0.01 M KNO_3 solution extracts from 66 contaminated soils representative of a wide range of field conditions in both North America and Europe revealed total Zn concentration from 0.01 to 21.96 mg L^{-1}.

The total Zn concentration in the soil solution was a function of the properties of the analyzed soils. Table 2 shows that the total Zn concentration in the soil solution decreased with increasing soil pH value. This is because the adsorption of Zn to the soil increases at higher pH (McBride et al. 1997; Bar-Tal et al. 1988; Msaky and Calvet 1990). It has been suggested that increases in metal retention with increasing soil pH may be due to adsorption, inner sphere complexation, and/or precipitation and multinuclear type reactions (Degryse et al. 2009). The solubility of Zn will decrease with increasing values of soil pH. This is due to the greater adsorptive capacity of the soil solid surfaces resulting from increased pH-dependent negative charge, the formation of hydrolyzed forms of Zn, chemisorption on calcite and co-precipitation in Fe oxides (Alloway 2009). The soil pH was the factor by which the Zn concentration in the soil solution was most influenced. We obtained a highly significant ($p < 0.0001$) linear relationship of total Zn concentration in the soil solution with soil pH (Table 3). The linear relationship between total Zn concentration in the soil solution and soil pH alone

Table 3 Linear regression equation of Zn and Zn^{2+} concentration in soil solution (mg L^{-1}) against soil pH, SOC and total Zn content in soil

Soil 7 % clay	Soil 13 % clay
$Zn(\pm 0.19) = 0.88(\pm 0.08) - 0.27(\pm 0.04)pH$	$Zn(\pm 0.15) = 0.57(\pm 0.07) - 0.18(\pm 0.03)pH$
$r = -0.77$ (< 0.0001)	$r = -0.71$ (< 0.0001)
$Zn(\pm 0.28) = 0.10(\pm 0.11) + 0.09(\pm 0.04)$total Zn	$Zn(\pm 0.19) = 0.04(\pm 0.08) + 0.07(\pm 0.03)$total Zn
$r = 0.37$ (0.0272)	$r = 0.38$ (0.0211)
$Zn(\pm 0.29) = 0.23(\pm 0.13) + 0.05(\pm 0.06)SOC$	$Zn(\pm 0.20) = 0.08(\pm 0.09) + 0.07(\pm 0.04)SOC$
$r = 0.15$ (n.s.)	$r = 0.27$ (n.s.)
$Zn^{2+}(\pm 0.13) = 0.52(\pm 0.06) - 0.16(\pm 0.03)pH$	$Zn^{2+}(\pm 0.09) = 0.35(\pm 0.04) - 0.11(\pm 0.02)pH$
$r = -0.70$ (< 0.0001)	$r = -0.71$ (< 0.0001)
$Zn^{2+}(\pm 0.17) = 0.04(\pm 0.07) + 0.07(\pm 0.02)$total Zn	$Zn^{2+}(\pm 0.12) = 0.02(\pm 0.05) + 0.04(\pm 0.02)$total Zn
$r = 0.42$ (0.0111)	$r = 0.41$ (0.0142)
$Zn^{2+}(\pm 0.18) = 0.12(\pm 0.08) + 0.04(\pm 0.03)SOC$	$Zn^{2+}(\pm 0.12) = 0.08(\pm 0.05) + 0.03(\pm 0.03)SOC$
$r = 0.20$ (n.s.)	$r = 0.20$ (n.s.)

The values in parentheses are the p (level of significance) values, *n.s.* no significance for $p < 0.05$

explains the 58.7 and 49.8 % of the variability in Zn concentration in the soil solution for soil with 7 and 13 % of clay particles, respectively.

In this study, we obtained significant linear relationship (at $p = 0.05$) between total Zn concentration in the soil solution and total Zn content in the soil (Table 3). The content of SOC in the soil did not have the influence on total Zn content in the soil solution (Tables 2, 3). The results are similar to other studies which reported that pH was more influential than any other single property in predicting Zn solubility while SOM did not have a significant effect (McBride et al. 1997; Stephan et al. 2008, Msaky and Calvet 1990).

Stephan et al. (2008), Sauvé (2001) and McBride et al. (1997) reported that the solubility of Zn can be linked to both H^+ and the total Zn content in the soil. We obtained a highly significant ($p < 0.001$) relationship between the total Zn concentration in the soil solution and both pH and total soil Zn ($p < 0.001$):

$$\begin{aligned} \mathrm{Zn}(\pm 0.16) &= 0.64(\pm 0.09) - 0.27(\pm 0.03)\mathrm{pH} \\ &\quad + 0.09(\pm 0.02)\text{total Zn} \\ R^2 &= 72.3\,\%(\text{for soil with } 7\,\%\text{ clay}) \\ \mathrm{Zn}(\pm 0.13) &= 0.39(\pm 0.07) - 0.18(\pm 0.03)\mathrm{pH} \\ &\quad + 0.07(\pm 0.02)\text{total Zn} \\ R^2 &= 64.5\,\%(\text{for soil with } 13\,\%\text{ clay}). \end{aligned}$$

We also evaluated the potential of organic matter to influence on total Zn concentration in the soil solution. The soil organic matter has a dual influence on the Zn concentration in the soil solution. It helps adsorb Zn to the solid phase, therefore decreasing concentrations in soil solutions. And inversely, higher soil organic matter content will also generate higher dissolved organic carbon content, and this would help complex Zn and lead to higher soil solution concentrations of Zn (Cavallaro and McBride 1984; Bar-Tal et al. 1988; Fotovat et al. 1997; Stephan et al. 2008).

The regression of total Zn concentration in the soil solution was improved significantly by addition of SOC to equation ($p < 0.001$):

$$\begin{aligned} \mathrm{Zn}(\pm 0.15) &= 0.54(\pm 0.11) - 0.27(\pm 0.03)\mathrm{pH} \\ &\quad + 0.09(\pm 0.02)\text{total Zn} + 0.05(\pm 0.03)\mathrm{SOC} \\ R^2 &= 74.5\,\%(\text{for soil with } 7\,\%\text{ clay}). \\ \mathrm{Zn}(\pm 0.12) &= 0.26(\pm 0.08) - 0.18(\pm 0.02)\mathrm{pH} \\ &\quad + 0.07(\pm 0.02)\text{total Zn} + 0.07(\pm 0.02)\mathrm{SOC} \\ R^2 &= 72.0\,\%(\text{for soil with } 13\,\%\text{ clay}). \end{aligned}$$

These relationships are shown in Fig. 1.

The soil texture also can affect the solubility of Zn in the soil (Dube et al. 2001; Kabata-Pendias 2004). However, the introduction of clay content into the model for Zn does not improve the prediction ability as shown in equation:

$$\begin{aligned} \mathrm{Zn}(\pm 0.14) &= 0.64(\pm 0.08) - 0.21(\pm 0.02)\mathrm{pH} \\ &\quad + 0.07(\pm 0.01)\text{total Zn} + 0.05(\pm 0.02)\mathrm{SOC} \\ &\quad - 0.15(\pm 0.03)\text{clay content} \\ R^2 &= 71.7\,\%(p < 0.001). \end{aligned}$$

Principal component analysis (PCA) reviled very strong negative correlation between pH and Zn and Zn^{2+}. Negative correlation was observed between clay and Zn, but it was much weaker than correlation with pH (Fig. 2).

There was very weak correlation between SOC and Zn. Two principal components explained about 62 % of total variability (PC1 45.7 % and PC2 16.7 %); it means that graphical presentation in Fig. 2 is enough meaningful for the evaluation of relationships between examined variables.

Solid/solution partition coefficient (K_d)

The dissolution of Zn can be also illustrated using a simple K_d partition coefficient, which is defined as:

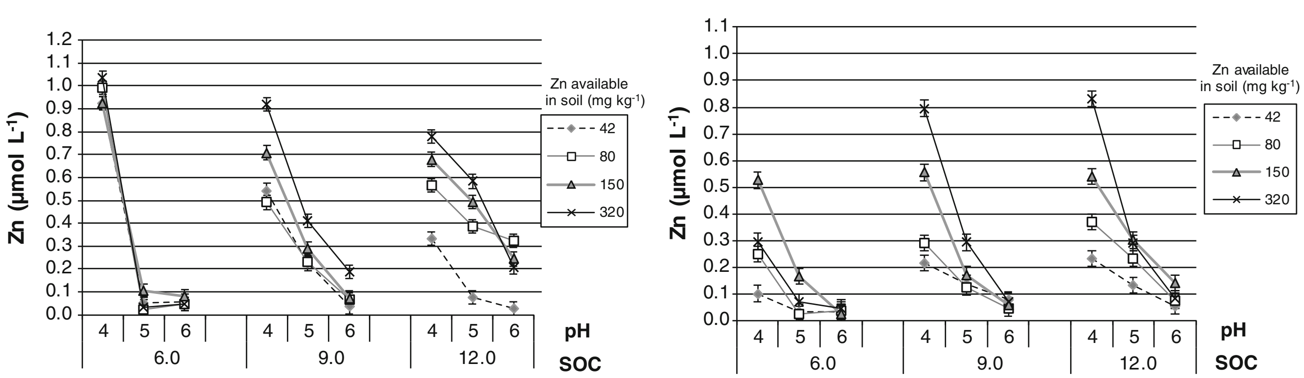

Fig. 1 The relationship between Zn concentration in the soil solution and soil pH, and content of soil organic carbon content (g kg^{-1} soil) in different content of Zn available in soil

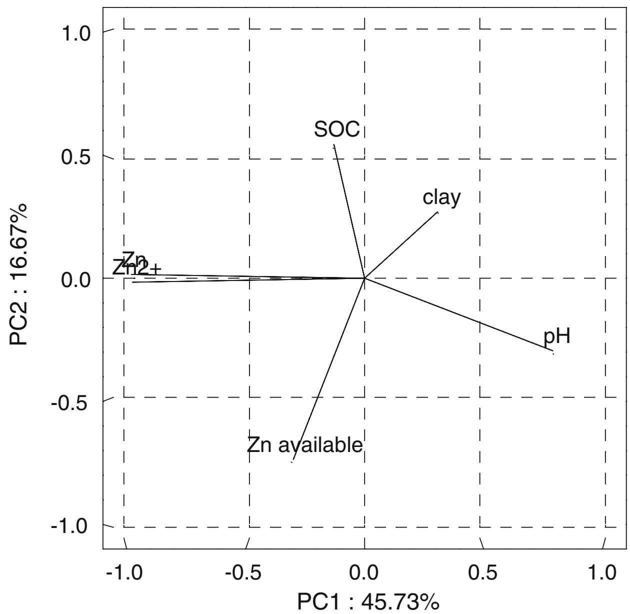

Fig. 2 Result of PCA relationship between Zn and environmental factors

$K_d = (\text{total soil Zn}/\text{total dissolved Zn})$

where in the present study, total soil Zn = soil Zn extracted by 1 mol L^{-1} HCl expressed in mg kg^{-1}, and total dissolved Zn = Zn in soil solution expressed in mg L^{-1}, and the resulting K_d is in L kg^{-1}.

The partition coefficient (K_d) is usually used to describe the distribution of metal between the solid and aqueous phases in environmental risk and fate models. The coefficient can be defined as the ratio of exchangeable metal in relation to metal in soil solution (Gooddy et al. 1995), the ratio of sorbed metal to dissolved metal under equilibrium conditions (Carlon et al. 2004) or the ratio of the total soil metal relative to metal in soil water extract Krishnamurti and Naidu 2002).

The K_d values were dependent on soil properties and ranged from 166 to 2,260 L kg^{-1}. Sauvé et al. (2000) for 298 soil samples obtained K_d values which ranging from 1.4 to 320,000 L kg^{-1}. However, other authors obtained lower K_d values: 100–500 L kg^{-1} Knight et al. (1998), 17–13,100 L kg^{-1} (Stephan et al. 2008) and 319–17,965 L kg^{-1} (Luo et al. 2006). The differences in obtained K_d values and cited K_d values are associated with the use of different extraction solutions. The values of K_d increased significantly with rising soil pH and total Zn content and decreased with increasing soil organic content (Table 4). Observed K_d values were significantly higher in soil with 13 % clay than in soil with 7 % clay (Table 4). Also, other authors have shown a positive correlation between K_d and the soil pH and Zn content in the soil (Stephan et al. 2008; Luo et al. 2006).

Zinc speciation—free Zn^{2+} in soil solution

The free metal activity is recognized as a main factor in understanding metal availability in soil environment (Peijnenburg et al. 2000). It is important to measure and predict the free metal activity in soil. The preferred method is to quantify and model the contributions of different soil properties such as pH, Zn content in soil or soil organic matter content, and then evaluate how they release to the activity of free Zn^{2+} in the soil solution (Sauvé 2001).

The activity of zinc free ions in the soil solution was determined using MINTEQA2 software. Estimated activity of Zn^{2+} ranged from 0.06 to 0.36 mg L^{-1} and was lower than the total concentration of this element in the soil solution (Table 2).

The activity of zinc in the soil solution depended on physical and chemical properties of analyzed soils (Table 2). The soil reaction was the factor by which the activity of free zinc ions was most influenced (Table 3). The activity of free Zn^{2+} in the solutions of analyzed soils were significantly higher at a lower value of soil pH, which was indicated by correlation coefficients r between the activity of Zn^{2+} in the soil solution and soil reaction ($r = -0.70$). Tipping et al. (2003) and Tye et al. (2003) showed that soil reaction is the main factor in determining the activity of free ions and associated bioavailability. The change of soil reaction to weakly acidic or acidic results in increased activity of Zn in the soil solution. This is caused both by increasing solubility of chemical bonds of these elements and decreasing sorption by soil colloids at low

Table 4 Solid/solution partition coefficient (K_d) according as soil properties (L kg^{-1})

Form of Zn	Soil reaction (pH_{KCl})			Content of organic carbon in soil (g kg^{-1})			Content of Zn in soil (mg kg^{-1})			
	pH 4	pH 5	pH 6	6.0	9.0	12.0	42.0	80.0	150.0	320.0
Soil 7 % clay	183	417	1,234	404	379	352	166	230	376	685
$LSD_{0.05}$	227			59			62			
Soil 13 % clay	317	629	2,260	1,120	553	478	373	495	543	1,036
$LSD_{0.05}$	188			122			108			

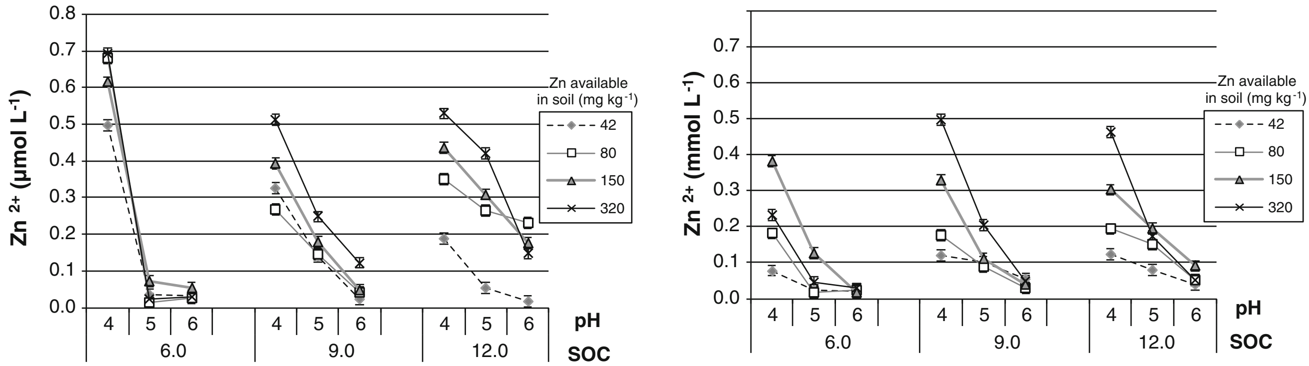

Fig. 3 The relationship between Zn^{2+} concentration in the soil solution and soil pH, and the content of soil organic carbon content (g kg^{-1} soil) in different content of Zn available in soil

values of soil pH (Stephan et al. 2008). The statistical analyses showed that the activity of zinc in the soil solution was positively correlated with the content of total Zn in soil (Tables 2, 3). The highest concentrations of Zn^{2+} in the solutions of analyzed soils were observed at highest content of Zn in soil, and these were two times higher when compared with the solutions of not contaminated soils (Table 2). The obtained relationships are confirmed by Nolan et al. (2003b) who reported that the concentration of Zn^{2+} in groundwater in Australian contaminated agricultural soils depended on the total content of zinc as well as the value of soil pH.

The pH and total soil Zn values can be combined together in order to construct a single highly significant ($p < 0.001$) predictive regression for free Zn^{2+}:

$$\begin{aligned} Zn^{2+}(\pm 0.09) &= 0.48(\pm 0.07) - 0.19(\pm 0.03)\text{pH} \\ &\quad + 0.05(\pm 0.02)\text{total Zn} \\ R^2 &= 63.5\,\%(\text{for soil with } 7\,\%\text{ clay}) \\ Zn^{2+}(\pm 0.06) &= 0.24(\pm 0.04) - 0.11(\pm 0.01)\text{pH} \\ &\quad + 0.04(\pm 0.01)\text{total Zn} \\ R^2 &= 65.5\,\%(\text{for soil with } 13\,\%\text{ clay}). \end{aligned}$$

The regression between free Zn^{2+} concentration in soil solution and total soil Zn content (Table 3) was improved significantly by the addition of pH to equation.

The activity of zinc increased with increasing contents of soil organic carbon; however, such relationship was not statistically significant (Tables 2, 3). Increasing content of SOC can increase the formation of organic metal complexes, while the solubility of metals may also increase (Aldrich et al. 2002). The introduction of soil organic carbon into the model for free Zn^{2+} improves the prediction ability from 63.5 to 71.3 % (soil with 7 % clay) and from 65.5 to 70.9 % (soil with 13 % clay) as shown in equations ($p < 0.001$):

$$\begin{aligned} Zn^{2+}(\pm 0.07) &= 0.18(\pm 0.05) - 0.11(\pm 0.03)\text{pH} \\ &\quad + 0.09(\pm 0.02)\text{total Zn} + 0.05(\pm 0.03)\text{SOC} \\ R^2 &= 71.3\,\%(\text{for soil with } 7\,\%\text{ clay}). \\ Zn^{2+}(\pm 0.07) &= 0.26(\pm 0.07) - 0.16(\pm 0.02)\text{pH} \\ &\quad + 0.07(\pm 0.01)\text{total Zn} + 0.04(\pm 0.02)\text{SOC} \\ R^2 &= 70.9\,\%(\text{for soil with } 13\,\%\text{ clay}). \end{aligned}$$

These relationships are shown in Fig. 3.

Soil texture had rather small effects on the activity of zinc in the soil solution (Tables 2, 3). Correlation coefficients indicated only weak relationships between clay content in soil and free Zn^{2+} in the soil solution. However, the results of statistical analysis (ANOVA) showed significantly higher total concentrations of free zinc ions in the soil solution of sandy soil (7 % clay) when compared with those of medium soils (13 % clay). Medium soils are characteristic of higher capacity of the sorption complex, and therefore, smaller amounts of zinc are released into the soil solution. On the other hand, in solutions of sandy soils—with lower capacity of the sorption complex—there are more Zn in their active forms. According to Rutkowska et al. (2006), the level of ion concentration in the soil solution depends on soil granulometric composition, and the concentration of Zn in the solutions of sandy soils is usually higher than in the solutions of soils with higher content of clay particles. The introduction of clay content into the model for Zn^{2+} does not improve the prediction ability as shown in equation:

$$\begin{aligned} Zn^{2+}(\pm 0.06) &= 0.37(\pm 0.06) - 0.13(\pm 0.01)\text{pH} \\ &\quad + 0.05(\pm 0.009)\text{total Zn} + 0.04(\pm 0.01)\text{SOC} \\ &\quad - 0.09(\pm 0.02)\text{ clay content} \\ R^2 &= 68.9\,\%(p < 0.001). \end{aligned}$$

Conclusion

The results of the present study showed that physical–chemical soil properties significantly differentiated the value of the K_d coefficient, the total concentration of zinc and the activity of free zinc ions in the soil solution. The activity of free Zn^{2+} in the soil solutions is very high and ranges from 64 to 68 % of the total Zn concentration in the soil solution. Soil reaction is the factor with the highest influence on the total concentration and activity of zinc free ions in the soil solution. The total concentration and activity of zinc free ions in the soil solutions increase significantly with rising soil acidity. The risk of contamination of soils and crops with zinc increases under the conditions of soils which are sandy, acidic and deficient in organic matter. Solid/solution partition coefficient (K_d) and multiple regression analysis of total Zn and free Zn^{2+} concentration in soil solution versus soil properties such as soil pH, total Zn content and soil organic carbon (SOC) content have been successfully used to predict the Zn mobility in soil and environmental risks in contaminated soils.

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