EFFECT OF ELEVATED CONCENTRATIONS OF CD AND ZN IN SOIL ON SPRING WHEAT YIELD AND THE METAL CONTENTS OF THE PLANTS

S. DUDKA
Trent University, Environmental and Resource Studies Program, Peterborough, Ontario, Canada, K9J 7B8

and

M. PIOTROWSKA and A. CHLOPECKA
The Institute of Soil Science and Plant Cultivation (I.U.N.G.), 24–100 Pulawy, Poland

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Abstract. The effect of increasing concentrations of Cd and Zn in a sandy soil on spring wheat (*Triticum vulgare* L.) yields and the metal contents of the plants was examined in a pot experiment to establish critical levels of these metals in soil. The metals were added (individually and jointly) to the soil as sulfates in the following doses (in $\mu g\ g^{-1}$, dry wt.): Cd – 2, 3, 5, 10, 15, 25, and 50; Zn – 200, 300, 500, 1000, 1500, 2500, and 5000. Cadmium added to soil did not affect yields of wheat. The Zn dose of 1000 $\mu g\ g^{-1}$ strongly reduced crop yields; at 1500 $\mu g\ g^{-1}$ Zn dose wheat did not produce grain. The metal contents of wheat increased with increasing concentrations of Cd and Zn in soil up to 10.3 and 1587 $\mu\ g^{-1}$ of Cd and Zn in straw, respectively. The concentrations of both metals were higher in straw than in grain by factors of 3–7 and 1.5–2 for Zn and Cd, respectively. The relationships between Cd and Zn contents of the plants and soils were best expressed by exponential equations. High concentrations of Zn in soils (1042 and 1542 $\mu g\ g^{-1}$) enhanced uptake of Cd by plants. The tested threshold concentrations of the metals in soils (3 $\mu g\ g^{-1}$ for Cd and 200– 300 $\mu g\ g^{-1}$ for Zn) are safe for Zn but are too high for Cd in terms of protecting plants from excessive metal uptake. The critical Cd content of sandy soil should not exceed 1.5 $\mu g\ g^{-1}$.

1. Introduction

Cadmium and Zn are elements having similar geochemical and environmental properties. Since Zn ores normally contain 0.1–5% of Cd, the processing and subsequent release of Zn to the environment is normally accompanied by Cd environemntal pollution (Adriano, 1986). Arable soils of industrialized areas are strongly affected by Cd and Zn pollution both through local and long-distance transport of contaminants and their deposition onto soil surface (Dudka, 1992; Dudka and Sajdak, 1992). In industrially polluted soils the ratio of Cd to Zn concentrations is around 1:100 (Dudka and Sajdak, 1992). Often the polluted soils are the source of polluting elements for crop plants grown in contaminated regions (Davies, 1992; Kabata-Pendias and Pendias, 1992).

The establishing of critical values for Cd and Zn contents of soil, that is concentrations above which plants are likely to take up high amount of the elements, is of interest because an excess of dietary intake of these metals might be deleterious to the health of a consumer. The critical concentrations for several elements (also known as maximum tolerable levels) were proposed at first in relation to sewage sludge application to land (Chumbley, 1971). The objective for setting these limits was to protect soil from rapid increase of metal contents and to assure the sustainable use of agricultural soils (Page *et al.*, 1988). Maximum tolerable levels for trace elements in agricultural soils proposed in various countries (Chumbley, 1971; Kloke, 1982; EEC, 1986; Page *et al.*, 1988; Kabata-Pendias and Pendias, 1992) range from (in $\mu g\ g^{-1}$): Cd 1.6 to 3; Cr 100 to 120; Cu 80 to 140; Ni 48 to 75; Pb 90 to 300; and Zn 150 to 300. The experimental data supporting these values as the scientifically proven concentrations are still limited. Studies on the threshold levels of elements conducted so far focused either on a single element (Roszyk *et al.*, 1988; Piotrowska and Dudka, 1992) or were carried out in nutrient solutions (Davis *et al.*, 1978; Wallace *et al.*, 1981; Wallace and Abou-Zamzam, 1989).

This research is part of a comprehensive study of the effect of industrially polluted soils on the trace metal contents of crop plants and plant yields (Dudka and Sajdak, 1992; Piotrowska and Dudka, 1992). The methods used include: pot, lysimetric, and plot experiments as well as studies of productive fields. The objective of this paper is to present the individual and joint effect of increasing concentrations of Cd and Zn in soils on yields of spring wheat and the metal contents of the plant in order to establish critical levels of these metals in light soils.

2. Materials and Methods

2.1. The Pot Experiment

The experiment was conducted in Mitscherlich's pots containg 7.5 kg of surface layer of sandy soil with the following properties: pH in KCl 6.6; particles <0.02 mm diameter – 12%; cation exchange capacity – 7.5 me. The experimental soil contained 0.8 and 42 $\mu g\ g^{-1}$ of Cd and Zn, respectively. The metals were applied to the soil individually and jointly as sulfates at the following doses ($\mu g\ g^{-1}$, dry wt. of soil): Cd – 2, 3, 5, 10, 15, 25, and 50; Zn – 200, 300, 500, 1000, 1500, 2500, and 5000. Two sets of the experiment were conducted: (i) soil without liming and (ii) soil with lime added at amounts sufficient to neutralize sulfates applied to soil. The untreated soil was used as a control. The treatments were replicated four times in a randomized design. The soil was equilibrated for 5 d after mixing with the metal compounds, and then spring wheat (*Triticum vulgare*, L., var. Eta) was planted. Plants were sown on April 26, 1991 (16 plants a pot) and harvested on August 5, 1991 at the full maturity stage. During the growth period the treatments were fertilized with NPK and watered with deionized water. Samples of spring straw and grain were collected and analyzed separately and after harvest the soil samples were also taken for pH analysis.

2.2. Chemical and Statistical Analysis

The plant material was dried in an air-forced oven at about 60 °C for 70–80 hours, weighed, and ground in a stainless steel mill. A 5.00 g subsample was dry ashed in ceramic crucibles in a muffle furnace at 450 °C for 16 hr, dissolved in 10 mL 50%

(vol/vol) HCl and diluted to 50 mL with double-distilled water. A representative sample of the experimental soil was air-dried and homogenized in an agate mortar. Three subsampls of 2 g were digested with $HClO_4$ and HF mixture. Following the evaporation to dryness on a hot plate the sampls were dissolved in 50% (vol/vol) HCl and diluted to 100 mL with 1% (vol/vol) HCl. The total Cd and Zn content of plant and soil samples was determined by flame atomic absorption spectroscopy (Perkin Elemer 403). The lower limits of analytical determination were as follows (in $\mu g\ g^{-1}$): soil – Cd 0.2, Zn 0.2; plants – Cd 0.01, Zn 0.04. Analytical precision of the ASS method was controlled by including several duplicate samples (10% of total). The Cd and Zn contents of the treated soil were estimated by summing up the amounts of the added metals and the original metal concentrations in the control soil.

One-way analysis of variance followed by Tukey's test was employed to compare element means and crop yields for each treatment (Koch ad Link, 1970). Regression analysis was used to relate the element contents of the plants to the element contents of the soil (Koch and Link, 1970).

3. Results and Discussion

The experimental soil contained a level of Zn (42 $\mu g\ g^{-1}$) typical for Polish soils while Cd concentration (0.8 $\mu g\ g^{-1}$) slightly exceeded natural Cd contents of these soils (Dudka, 1992). At the beginning of the experiment the soil had a neutral reaction (pH_{KCL} 6.6). During the experiment pH of the control soil did not change and pH of the soil with highest doses of Zn and Cd + Zn decreased by about 0.6–0.7 units. Since we expected a strong effect of sulfates introduced to the soil on a soil pH, we conducted two sets of experiments: treatments with no lime added and treatments with lime added to soil at amounts sufficient to neutralize the sulfates. However, the soil had a good buffering capacity and soil pH did not differ markedly between the unlimed and limed treatments. As a result no significant differences between the two series of the experiment were observed in either crop yields or the metal contents of the plant. Therefore, only results for the unlimed soil treatments are reported in the paper.

Addidition of Cd to soil did not affect yields of spring wheat. The differences in crop yields between treatments were not significant (Table I) and can be attributed to random variability within treatments rather than to the effect of the studied factor. Wheat growing in the Cd treated soil did not show any symptoms of chlorosis, necrosis or any disturbances in growth. Plants are known to tolerate relatively high concentrations of Cd without visible symptoms of toxicity (Adriano, 1986; Chaney, 1983; John and Van Laerhoven, 1976). The results of this paper show that Cd concentrations in vegetative parts of wheat even 25 times higher than the control level (Table II) were not harmful to the plants.

In contrast increasing doses of Zn strongly affected the plant growth. In the treatment of a Zn dose of 1000 $\mu g\ g^{-1}$ the yields of straw and grain were reduced

TABLE I

Yields (mg/pot) of spring wheat; means of four replicates ± standard deviations

Treatment	Cd		Zn		Cd + Zn	
	Straw[1]	Grain[1]	Straw[2]	Grain[2]	Straw[2]	Grain[2]
Control	17.7±0.6	22.5±1.1	17.7^{a}±0.6	22.5^{a}±1.1	17.7^{a}±0.6	22.5^{a}±1.1
M2	15.7±1.1	21.8±1.2	16.2^{a}±1.3	22.1^{a}±1.5	16.2^{a}±0.6	21.9^{a}±1.1
M3	15.2±1.2	22.6±1.7	17.0^{a}±0.6	21.6^{a}±0.8	16.6^{a}±1.8	22.9^{a}±1.6
M5	15.4±1.4	22.3±2.7	18.4^{a}±1.1	21.1^{a}±0.8	18.2^{a}±1.3	21.4^{a}±2.1
M10	17.1±2.1	23.8±3.1	12.4^{b}±0.8	14.0^{b}±1.8	9.6^{b}±0.8	6.6^{b}±1.2
M15	14.2±1.0	19.8±1.1	6.8^{c}±0.4	n.d	5.3^{c}±0.9	n.d.
M25	15.6±1.3	22.8±1.8	n.d	n.d	n.d.	n.d.
M50	16.8±0.7	23.0±1.6	n.d	n.d	n.d.	n.d.

[1] – means are not significantly different at *P<0.05*; [2] – means followed by various letters are significantly different at *P<0.05*.
Metal contents of control soil ($\mu g\ g^{-1}$): Cd – 0.8, Zn – 42
Doses of metals ($\mu g\ d^{-1}$, dry wt.): M2 – Cd 2, Zn 200; M3 – Cd 3, Zn 300; M5 – Cd 5, Zn 500; M10 – Cd 10, Zn 1000; M15 – Cd 15, Zn 1500; M25 – Cd 25, Zn 2500; M50 – Cd 50, Zn 5000.

TABLE II

Cadmium contents ($\mu g\ g^{-1}$) of spring wheat; means[a] of four replicates ± standard deviations

Treatment	Cd		Cd + Zn	
	Cd-s	Cd-g	Cd-s	Cd-g
Control	0.40^{a}±0.00	0.28^{a}±0.05	0.30^{a}±0.05	0.25^{a}±0.05
M2	1.08^{b}±0.05	0.85^{b}±0.06	0.80^{b}±0.22	0.75^{b}±0.13
M3	0.93^{b}±0.22	0.75^{b}±0.17	1.00^{b}±0.10	0.80^{b}±0.12
M5	1.93^{c}±0.19	1.25^{c}±0.13	1.70^{c}±0.14	1.10^{b}±0.14
M10	3.23^{d}±0.25	2.10^{d}±0.14	5.65^{d}±0.93	4.60^{c}±0.95
M15	4.60^{e}±0.38	2.38^{d}±0.23	9.90^{e}±0.97	n.d.
M25	6.38^{f}±0.61	3.10^{e}±0.27	n.d.	n.d.
M50	10.33^{g}±0.53	4.05^{f}±0.06	n.d.	n.d.

[a] – means followed by various letters are significantly different at *P<0.05*
Metal contents of control soil ($\mu g\ g^{-1}$): Cd – 0.8, Zn – 42
Doses of metals ($\mu g\ d^{-1}$, dry wt.): M2 – Cd 2, Zn 200; M3 – Cd 3, Zn 300; M5 – Cd 5, Zn 500; M10 – Cd 10, Zn 1000; M15 – Cd 15, Zn 1500; M25 – Cd 25, Zn 2500; M50 – Cd 50, Zn 5000; s – straw; g – grain.

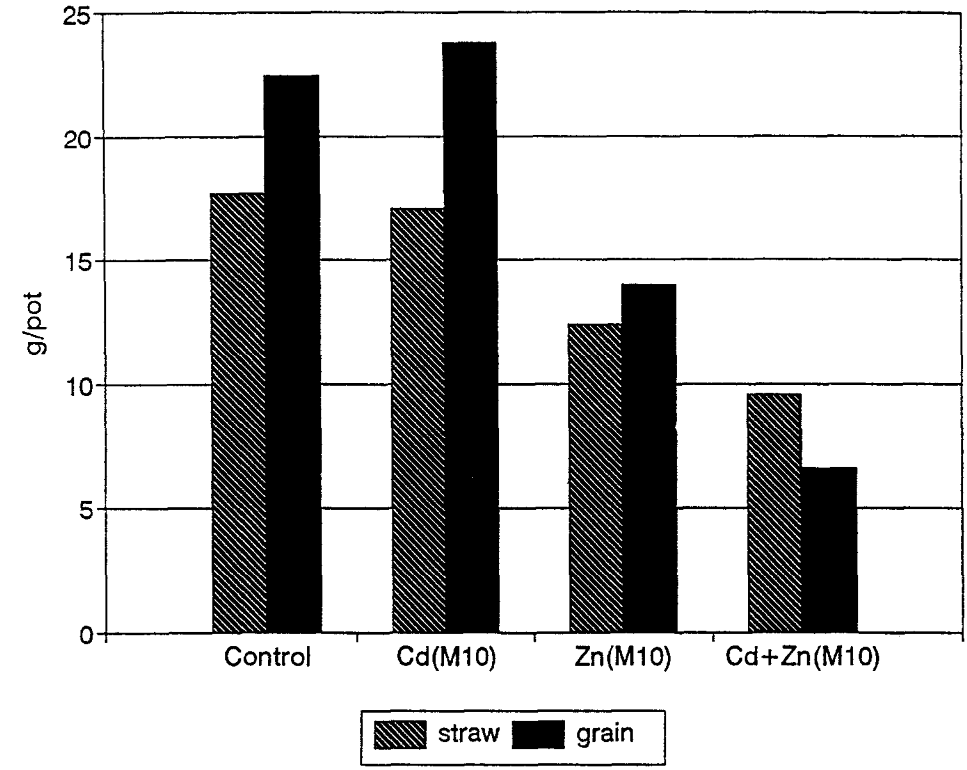

Fig. 1. Effect of Zn + Cd on wheat yield; doses of metals: Cd(M10) – 10 $\mu g\ g^{-1}$ of Cd; Zn(M10) – 10 $\mu g\ g^{-1}$ of Cd and 1000 $\mu g\ g^{-1}$ of Zn.

by about 30% and 40% respectively, compared to the control treatment (Table I; Figure 1). Further increase of Zn doses was lethal for plants; at the Zn dose of 1500 $\mu g\ g^{-1}$ plants did not produce grain; higher doses of the metal killed the plants at an early stage of growth (Table I). In the treatments with joint application of Cd and Zn to the soil the reduction of plant growth was stronger than in the treatments with addition of Zn only (Table I; Figure 1). However, the Cd-Zn interaction appeared only at the concentrations of Zn when Zn alone was toxic to the plants.

With increasing doses of the metals to the soil, Cd and Zn concentrations in the plants increased (Table II and III). However, changes in Zn content of the plants were more parallel to the changes in the metal level in the soils (Table III) than those of Cd (Table II). Cadmium contents of the plant were several times lower than the element concentrations in corresponding soils. The ratio between a level of Cd in the treated plants and in the soils (called Accumulation Index, AI) was 0.2 to 0.4 for the straw and 0.08 to 0.3 for the grain. In general, the higher the Cd content of the soil the lower the AI was. Many authors share the opinion that AI of Cd is normally 1 to 10 (Adriano, 1986; Kabata-Pendias and Pendias, 1992; Lüben and Saurbeck, 1991; Sauerbeck, 1991). However, AIs for Cd of about 1 and higher

TABLE III

Zinc contents ($\mu g\ g^{-1}$) of spring wheat; means[a] of four replicates ± standard deviations

Treatment	Zn		Zn + Cd	
	Zn-s	Zn-g	Zn-s	Zn-g
Control	24.3[a]± 2.4	36.3[a]± 4.1	26.4[a]± 3.2	36.3± 4.1
M2	240.0[b]± 27.4	92.3[b]± 1.7	218.3[b]±10.3	84.3[b]± 5.5
M3	318.8[c]± 21.0	97.5[b]± 5.0	291.3[c]±15.5	102.3± 9.0
M5	513.3[d]± 58.0	140.0[c]±14.1	532.5[d]±40.3	141.2[b]± 8.5
M10	1587.5[e]±165.2	212.5[c]±13.2	1500.0[e]±70.7	215.0±10.8
M15	1387.5[e]±138.5	n.d.	1362.5[e]±97.8	n.d.

[a] – means followed by various letters are significantly different at $P<0.05$
Metal contents of control soil ($\mu g\ g^{-1}$): Cd – 0.8, Zn – 42
Doses of metals ($\mu g\ d^{-1}$, dry wt.): M2 – Cd 2, Zn 200; M3 – Cd 3, Zn 300; M5 – Cd 5, Zn 500; M10 – Cd 10, Zn 1000; M15 – Cd 15, Zn 1500; M25 – Cd 25, Zn 2500; M50 – Cd 50, Zn 5000; s – straw; g – grain.

are observed in young plants, especially if they grow in a nutrient solution rather than in soil. This index for mature plants grown over contaminated soil is, as a result of this experiment and those of other studies (Chlopecka, 1992; Piotrowska and Dudka, 1992), well below 1.

For unit increase of Zn content of the soil the metal content of the wheat straw also increased by a unit up to 1042 $\mu g\ g^{-1}$ of Zn in the soil. Changes of Zn content of wheat grain were much more moderate (Table III). Accumulation index varied from 0.1 to 0.4. The differences in Cd and Zn contents of the grain and straw indicate the inhibition of the transport of these elements to generative parts of the plant. The fixation of potentially toxic elements in vegetative parts is one of the known mechanisms of plant tolerance to excesses of trace metals (Cumming and Tomsett, 1992).

The level of Cd in wheat was significantly increased by the presence of high concentration of Zn in soils (1042 and 1542 $\mu g\ g^{-1}$) in the Cd-Zn treatments compared to the Cd treatments without Zn (Table II; Figure 2); but no significant effect of Cd on Zn content of the plants was observed (Table III). The changes of Cd contents of wheat apparently resulted from the enhancement of Cd uptake. However they can be partly related to differences in the crop yield between treatments. At the lower doses of metals to the soil (M2 to M5) the Cd contents of wheat in the Cd and Cd-Zn treatments were not significantly different, which implies that no interaction between Cd and Zn occurred. The Zn effect on Cd uptake by the plants appeared at the Zn level in soil, at which Zn was toxic to plants. This suggests that the elevated Cd level in wheat was caused by reducing the ability of the Zn-poisoned plants

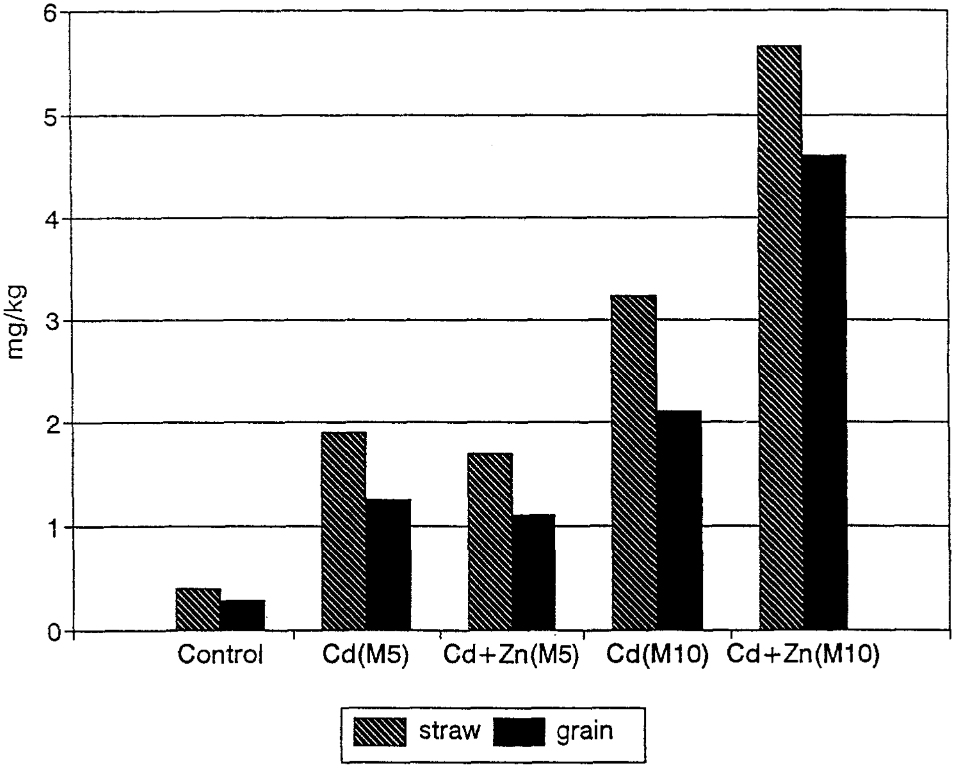

Fig. 2. Effect of Zn + Cd on Cd content of wheat; doses of metals: Cd(M5) – 5 μg g^{-1} of Cd; Cd+Zn(M5) – 5 μg g^{-1} of Cd and 500 μg g^{-1} of Zn; Cd(M10) – 10 μg g^{-1} of Cd; Cd + Zn(M10) – 10 μg g^{-1} of Cd and 1000 μg g^{-1} of Zn.

to control Cd uptake. The lack of interaction between Cd and Zn at the proposed maximum tolerable concentrations of the metals in soils indicates that threshold values for both metals can be the same regardless of whether Cd and Zn are applied individually or jointly to soil.

Even though the plants apparently have mechanisms of Cd uptake control, the level of the metal in wheat grown in the Cd-treated soils increased to values that can be harmful to animals if they eat such plants. According to some estimations (Chaney, 1983) concentrations of Cd as low as 0.5 μg g^{-1} in forage can be chronically toxic to animals. The abilitity of cultivated plants to tolerate high contents of Cd without showing any symptoms of toxicity creates a serious problem in terms of animal and human poisoning from this metal through the food chain (Chaney, 1983). Cadmium therefore is an element whose movement through the food chain is not controlled by a soil-plant barrier. Although the results of a pot experiment cannot be transferred directly to field conditions, it seems that 3–5 μg g^{-1} of Cd proposed by many authors (Page *et al.*, 1988; Kabata-Pendias and Pendias, 1992) as maximum tolerable levels of the metal in soils is too high to

TABLE IV

Relationship between Cd and Zn in wheat (y) and soils (x) for treatments with the metals added individually

y	x	Equations[a]	100 (r^2)
Cd-s	Cd	$y = 0.436x^{0.818}$	98.3
Cd-g	Cd	$y = 0.365x^{0.660}$	97.4
Zn-s	Zn	$y = 0.315x^{1.184}$	98.2
Zn-g	Zn	$y = 4.602x^{0.542}$	98.9

[a] Significant at $P<0.05$; s – straw; g – grain.

protect plants from excessive uptake. This concentration should not be higher than 1.5 μg g^{-1}. This conclusion is supported by the results of a regression analysis. We found a strong relationship between the metal contents of wheat and the soil as described by exponential equations (Table IV). The concentrations of Cd in wheat as estimated by the equations in Table IV would be 0.48 and 0.60 μg g^{-1} for grain and straw respectively if the Cd content of the soil were 1.5 μg g^{-1}. We consider these concentrations to be low enough values from the point of view of preserving the proper crop quality.

Zinc is a metal which is phytotoxic at concentrations that are still safe for animals eating affected plants (Gough *et al.*, 1979; Chaney, 1982). Animals can tolerate as much as 500–1000 μg of Zn per g of forage. At the concentrations considered (Kabata-Pendias and Pendias, 1992; Page *al.* 1992) as threshold values for Zn in soils (200–300 μg g^{-1}, M2 and M3 treatments had concentrations close to these values) neither crop yield reduction or excessive concentrations of Zn in plants appeared. In this study Zn toxicity symptoms were observed in the M10 treatment (Figure 1) accompanied by very high Zn content of wheat (Table III). Concentrations of Zn in wheat grown in soil having 300 μg g^{-1} can be predicted based on regression equations (Table IV). They would be 101 and 270 μg g^{-1} for grain and straw, respectively. Therefore, the concentration of 300 μg g^{-1} Zn in soils is still a safe level of the metal both in terms of its contents un plants and its effect on crop yields.

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