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Transport of Cd, Cu, Pb and Zn in a calcareous soil under wheat and safflower cultivation— A column study

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ABSTRACT

Anthropogenic release of heavy metals (HMs) into the environment has resulted in a continuous buildup of HMs in agricultural soils. On the one hand, uptake of HMs by crop plants may lead to food chain transfer to humans, and on the other, leaching of HMs with deep seepage may cause groundwater contamination. The objectives of this study were to assess the mobility of cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn) under two common crop plants with different rooting systems, wheat (*Triticum aestivum*) with fibrous roots, and safflower (*Carthamus tinctorious*) with a taproot system in a calcareous silty clay loam soil. The study was conducted with 50 cm long undisturbed soil columns (Typic Haplocalcid) extracted from a wheat and a safflower field located in the same unit of soil type. The top 10 cm of half of the columns were artificially contaminated with Cd, Cu, Pb, and Zn at concentrations of 15, 585, 117 and 1094 mg kg^{-1}, respectively. Half of the contaminated and uncontaminated columns were planted with wheat and the other half with safflower according to their previous cultivation history. Discharge was collected continuously. After the crops were harvested, soil samples were collected at 10-cm intervals and analyzed for HNO_3- and DTPA-extractable metals. Plants enhanced the displacement of metals into the subsoil. Safflower resulted in larger concentrations at deeper depths than wheat. Metal concentrations were significantly ($P<0.05$) higher in discharge from contaminated than from uncontaminated columns. Because discharge was reduced in the presence of plants due to transpiration, total amounts of metals leached were in general larger in fallow than treatments with plants. The only exception was the leaching of Zn from wheat columns, which was larger under plants than under fallow. Plants did not only affect metal transport velocity of mobile fraction through actual root activity, but also through effects on soil properties during previous cultivation history, as there were clear differences in metal leaching between wheat and safflower soils from fallow columns. These were metal-dependent, indicating that these effects were not only related to different effects on soil structure by the root systems, but also to chemical soil properties.

1. Introduction

Soil pollution by heavy metals (HMs) continues to create serious environmental risks (Hinz and Selim, 1994; Richards et al., 1998; Schwab et al. 2002). Industrial and agricultural activities have released large amounts of HMs into soils (Li and Li, 2001). The metals added to the soil may eventually end up in the food chain or cause contamination of groundwater resources. In Isfahan, located in central Iran, for example, a steel factory and other factories release their wastewater into the surrounding lowland areas where groundwater levels are less than 2 m (Shirani, 1996). Also, large-scale applications of sewage sludge and fertilizers on agricultural lands can be important sources of soil contamination by HMs (Amini et al., 2005).

The mobility of HMs in soils has been investigated for several decades (Giordano and Mortvedt, 1976; Richards et al., 2000). Many researchers have concluded that there is little evidence for HM leaching through the soil into the groundwater (Chang et al., 1984; Higgins, 1984; Williams et al., 1987). However, most of these studies were conducted using columns of homogenized soil (Giordano and Mortvedt, 1976; Emmerich et al., 1982) and often the fact that no significant increase in HM concentrations below the contaminated

Abbreviations: AAS, atomic absorption spectrometry; DTPA, di-ethylene-triamine-penta-acetic acid; HM, heavy metal; ICP, inductively coupled plasma; M, metal application; S, planted safflower columns; Sf, fallow safflower columns; TDR, time domain reflectometry; W, planted wheat columns; Wf, fallow wheat columns.

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Table 1
Average and standard deviations of soil chemical and physical properties.

	Wheat farm			Safflower farm		
Depth (m)	0–0.25	0.25–0.45	0.45–0.60	0–0.25	0.25–0.45	0.45–0.60
pH	7.7 ± 0.1	7.9 ± 0.08	7.9 ± 0.06	7.6 ± 0.05	7.7 ± 0.1	7.8 ± 0.05
EC (dS m^{-1})	10.5 ± 2.45	6.6 ± 0.68	6.5 ± 0.48	9.8 ± 1.64	7.8 ± 1.99	5.9 ± 2.25
$CaCO_3$ (%)	38.2 ± 0.85	35.6 ± 0.92	37.6 ± 1.11	37.2 ± 1.68	35.9 ± 0.5	36.2 ± 1.42
Cd (mg kg^{-1})	1.6 ± 0.60	1.7 ± 0.50	1.7 ± 0.34	1.6 ± 0.52	1.7 ± 0.34	1.6 ± 0.50
Cu (mg kg^{-1})	33.4 ± 5.27	28.5 ± 1.71	27.1 ± 2.1	31 ± 1.97	29.5 ± 1.66	28.1 ± 1.56
Pb (mg kg^{-1})	20.3 ± 2.52	16.5 ± 0.70	15.3 ± 1.10	19.3 ± 1.51	15.5 ± 0.90	14.1 ± 1.12
Zn (mg kg^{-1})	64.5 ± 5.10	59.1 ± 4.90	58.1 ± 3.10	64.3 ± 5.51	62.1 ± 5.05	57.3 ± 3.2
Cl (%)	2.4 ± 0.51	1.6 ± 0.27	1.6 ± 0.17	2.1 ± 0.51	1.6 ± 0.29	1.1 ± 0.20
CEC (cmol kg^{-1})	14.8 ± 0.83	13.7 ± 0.44	14.6 ± 0.66	13.8 ± 0.71	14.6 ± 0.47	14.3 ± 0.80
Organic matter. (%)	1.0 ± 0.08	0.7 ± 0.10	0.7 ± 0.06	0.5 ± 0.03	0.3 ± 0.08	0.4 ± 0.03
Sand (g kg^{-1})	177.0 ± 14.1	172.0 ± 21.0	177.0 ± 14.0	179.0 ± 15.2	171.0 ± 11.2	182.0 ± 5.1
Silt (g kg^{-1})	434.0 ± 23.2	425.0 ± 21.4	431.0 ± 31.1	431.0 ± 21.2	424.0 ± 12.1	433.0 ± 22.
Clay (g kg^{-1})	389.0 ± 21.0	403.0 ± 32.0	392.0 ± 31.0	390.0 ± 23.0	405.0 ± 31.0	385.0 ± 12.0
Bulk density (Mg m^{-3})	1.3 ± 0.13	1.4 ± 0.08	1.4 ± 0.02	1.32 ± 0.15	1.43 ± 0.09	1.45 ± 0.04

Average of three replications ± standard deviation.

topsoil was found was considered as evidence that the metals were immobile (Chang et al., 1984; Dowdy et al., 1991). In many of these studies up to 40–50% of the applied metals were not recovered. The reasons for poor recoveries were attributed to tillage dispersion (Williams et al., 1987), incomplete analytical recovery and changes in bulk density (Chang et al., 1984). Another initially overlooked possibility is that metals can be leached by preferential flow and transport processes through macro-structures such as cracks, wormholes, plant root channels and other pathways of high hydraulic conductivity. Preferential flow can greatly increase the mobility and velocity of heavy metals and solute transport through the soil (Camobreco et al., 1996; Richards et al., 1998; Schwab et al., 2002). The effects of preferential flow can be particularly dramatic in clay soils that form cracks upon drying, which increase their hydraulic conductivity by several orders of magnitude while the matrix remains almost impermeable (Topp and Davis, 1981). Another factor that can enhance metal mobility is binding with organic ligands or colloids, particularly at near-neutral and high pH values (Camobreco et al., 1996; Richards et al., 1997; McBride, 1998).

Vegetation is another important factor influencing the mobility of metals in soil, directly as well as indirectly (Meek et al., 1990; Caron et al., 1996; Madrid et al., 2003; Banks et al., 2006; Caetano et al., 2008; Fernandez et al., 2008). Plants may increase metal mobility through the formation of preferential pathways along root channels or the complexation of metals with root exudates in the rhizosphere. They may also retard metal leaching through reducing deep seepage by taking up water, adsorption of metals to root surfaces, plant uptake of metals, and stimulated microbial immobilization in the rhizosphere (Tyler and McBride, 1982; Schwab et al., 2002).

The information about HM transport under plants with different rooting systems is limited, especially in soils with high pH and clay content, in which cationic metals are generally considered to be immobile. The objective of this study was to investigate the mobility of Cd, Cu, Pb and Zn under two crops with different rooting systems, i.e., wheat with a fibrous root system and safflower with a taproot system in a typical calcareous soil of central Iran. For this purpose, we performed a greenhouse experiment with undisturbed soil columns. In order to separate direct plant effects on metal mobility from indirect effects exerted via the influence of plants on soil structure, the soils were taken from two fields with the same type of soil, but different previous cultivation histories, i.e. a field that had been cultivated with wheat and another with safflower. Half of the columns were kept fallow, while the other columns were planted with two respective crops. This study is an initial assessment in which a wide range of measurements were made in hopes that they show what factors were associated with metal transport.

2. Materials and methods

The study was conducted using 24 undisturbed soil columns of 22.5 cm in diameter and 50 cm in depth in a greenhouse of Isfahan University of Technology. The soils—fine, mixed, thermic, Typic Haplocalcid—(Soil Survey Staff, 2003) were sampled from the same unit of soil type on two nearby fields at Kabotarabad Research Station of Isfahan Agricultural Research Center, 40 km southeast of Isfahan, central Iran (55° 50′ 16″ to 55° 50′ 26″ longitude and 32° 30′ 14″ to 32° 30′ 44″ latitude) with an elevation of 1750 m and mean annual precipitation of 145 mm. One field had been cultivated with safflower

Table 2
Freundlich isotherm parameters obtained by batch experiment for different depths.

$Metal_{Depth\ (cm)}$	k_F ($mg_{metal}^{(1-\beta)}$ $(cm^3)^\beta$ mg_{soil}^{-1})		β (−)		r^2 [a]	
	W[b]	S	W	S	W	S
Cd_{0-15}	20.4	18.6	0.49	0.58	0.83	0.89
Cd_{15-30}	24.6	21.8	0.50	0.49	0.92	0.89
Cd_{30-50}	29.5	28.8	0.59	0.51	0.99	0.93
Cu_{0-15}	48.9	53.87	0.49	0.96	0.98	0.99
Cu_{15-30}	38.0	50.1	0.45	0.37	0.86	0.98
Cu_{30-50}	69.2	60.2	0.65	0.83	0.79	0.80
Pb_{0-15}	49.8	49.7	1.00	1.00	0.98	0.87
Pb_{15-30}	49.8	49.7	0.99	1.00	0.95	0.89
Pb_{30-50}	49.8	49.8	1.00	1.00	0.94	0.96
Zn_{0-15}	29.1	27.3	1.09	1.11	0.92	0.99
Zn_{15-30}	39.8	36.3	0.45	0.27	0.80	0.99
Zn_{30-50}	47.8	39.0	0.43	0.33	0.89	0.88

[a] r^2: coefficient of determination.
[b] W and S stand for "wheat soil" and "safflower soil", respectively.

Table 3
Water balance for different treatments.

Treatment	Soil storage change (mm)	*E* (mm)	Discharge (mm)
W[a]	−12.7 ± 5.1bc[b]	382.0 ± 3.7a	193.0 ± 8.8c
Wf	7.0 ± 5.6a	260.0 ± 8.1c	335.0 ± 13.6a
W + M	−7.0 ± 5.7b	336.0 ± 20.2b	245.0 ± 14.3b
Wf + M	10.1 ± 6.1a	267.0 ± 33.1c	332.0 ± 29.5a
S	−17.0 ± 8.4c	391.0 ± 11.4a	180.0 ± 19.8c
Sf	5.0 ± 3.0a	275.0 ± 2.3c	318.0 ± 1.5a
S + M	−9.0 ± 7.0b	367.0 ± 5.9a	212.0 ± 12.9c
Sf + M	10.2 ± 1.3a	273.0 ± 3.1c	325.0 ± 5.8a
Total irrigation = 588.5 mm			

Average of three replications ± standard deviation.
[a] W: planted wheat columns; Wf: fallow wheat columns; S: planted safflower columns; Sf: fallow safflower columns; M: metal application; E: evaporation for fallow and evapotranspiration for planted columns.
[b] In each column means with similar letters are not significantly different at 0.05 level according to the LSD test.