Effects of forms and rates of potassium fertilizers on cadmium uptake by two cultivars of spring wheat (*Triticum aestivum*, L.)

Zhong-Qiu Zhao^a, Yong-Guan Zhu^{a,*}, Hui-Ying Li^{b,c}, Sally E. Smith^c, F. Andrew Smith^c

^aResearch Center for Eco-environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

^bInstitute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang, China

^cDepartment of Soil and Water, The University of Adelaide, Glen Osmond SA5064, Australia

Received 9 December 2002; accepted 6 March 2003

Abstract

A greenhouse pot experiment was conducted to study the influence of potassium fertilizers in different forms and rates on cadmium (Cd) uptake by two cultivars of spring wheat (*Triticum aestivum*, L.): Brookton and Krichauff. Potassium fertilizers were added to soil at four levels: 0, 55, 110 and 166 mg K kg⁻¹ soil as KNO₃ (N), KCl (C) or K₂SO₄ (S). CdCl₂ was added to all the treatments at a uniform rate equivalent to 15 mg Cd kg⁻¹ soil. Plant shoot and root dry weights (DW) of both cultivars were reduced significantly by the addition of K-fertilizer in C and S treatments but there were only marginal changes in the N treatments. The Cd concentrations in shoots and whole plants increased significantly ($P < .001$) with increasing K addition, from 37.5 to 81.4 mg kg⁻¹ and from 42.9 to 86.8 mg kg⁻¹ for Brookton and Krichauff, respectively. However, no obvious effect was observed in the N treatments, except for the highest K level (K3) where there was a sharp increase in Cd concentration compared to the lower additions. Forms of K-fertilizers significantly influenced the Cd concentrations in plant shoots and roots ($P < .001$), but there was no significant difference between C and S treatments. This experiment showed that anions Cl⁻ and SO₄²⁻ increase Cd uptake by plants, which can be interpreted as Cl⁻ and SO₄²⁻ complexing readily with Cd²⁺ and thereby increasing the bioavailability of Cd²⁺ in soils. The effect of potassium itself on plant uptake of Cd was also observed. We suggest that when applying potassium fertilizer to Cd-contaminated soils, the forms and rates should be considered.

© 2003 Elsevier Science Ltd. All rights reserved.

Keywords: Anion; Potassium fertilizers; Cadmium uptake; Spring wheat

1. Introduction

Cadmium (Cd), one of the nonessential and toxic heavy metals, can be transferred via the food chains and accumulate in human bodies. Cadmium in the body can result in many health problems such as itai-itai disease, renal dysfunction, liver damage, lung edema, anemia and hypertension (Basta et al., 1998). With the addition of Cd-containing manures, fertilizers, sewage, biosolids and other soil amendments and atmospheric deposition, soil contamination is becoming serious over large areas. Several studies reported that environmental contamination with cadmium caused serious human health problems in some parts of China (Cai et al., 1990; Nordberg et al., 1997). Accordingly,

soil contamination with Cd and other heavy metals and plant uptake of those heavy metals has been one of the focuses of environmental science because of their transportation and accumulation in food chains.

Many factors affect cadmium transport and accumulation in plant–soil systems, such as soil pH, soil redox potential, cation exchange capacity, plant species and fertilizer application, etc. (Chaney and Hornick, 1978). Nitrogen (N) and phosphorus (P) fertilizer application may increase Cd accumulation in plants (Oliver et al., 1993; Grant and Bailly, 1997; Basta et al., 1998), and the effect of different N sources and rates vary markedly (Eriksson, 1990; Willaert and Verloo, 1992; Mair et al., 2002). Much work has been done by Zhu (2001) and Zhu et al. (1999, 2000, 2002) on the interaction between potassium (K) and ¹³⁷Cs, which has shown that K significantly affected ¹³⁷Cs uptake by plants. Few studies have yet been done on the relationship between potassium fertilizer and Cd uptake by plants. Sparrow et al. (1994) showed that addition of K as KCl increased Cd

* Corresponding author. Tel.: +86-10-6293-6940; fax: +86-10-6292-3563.

E-mail address: ygzhu@mail.rcees.ac.cn (Y.-G. Zhu).

concentrations in potato tubers compared to the equivalent amount of K as K_2SO_4 . Grant et al. (1996) suggested that KCl increased Cd concentration in barley grain. In contrast, a field experiment conducted by McLaughlin et al. (1995) showed no influence of various K forms (KCl, K_2SO_4) on Cd concentrations in potato tubers.

K fertilizers are always accompanied by anions such as chloride and sulfate, which have been reported to increase Cd concentrations in plants. Some investigations have been carried out on effects of chloride and sulfate on Cd uptake by plants. Bingham et al. (1984, 1986) first reported that chloride and sulfate increased Cd uptake by Swiss chard (*Beta vulgaris* L.). Li et al. (1994) and McLaughlin et al. (1994) found in field experiments that soil salinity (chloride) was an important factor influencing Cd concentrations in field crops. Recently, a field survey conducted by Norvell et al. (2000) showed that the accumulation of Cd in durum wheat grain was strongly and positively associated with soil salinity. Smolders and McLaughlin (1996) and Smolders et al. (1996) demonstrated that Cd^{2+} complexes with Cl to form $CdCl_n^{2-n}$, which appeared to be available to plants. Both solution culture and pot experiments using soil, however, suggested that addition of sulfate did not affect, or only marginally increased Cd uptake by plants, although addition of sulfate decreased free Cd^{2+} concentration in soil solution markedly or increased Cd concentrations in soil solution.

As an important macronutrient, and one of the dominating factors of soil cation exchange capacity (CEC), K may possibly influence Cd transportation and accumulation in soil–plant systems. In the present experiment, we investigated the effects of K fertilizers in different forms and at different rates on the biomass and Cd concentration in two different cultivars of spring wheat.

2. Materials and methods

2.1. Soils

This study involved a pot experiment (Table 1). A loamy soil (0–25 cm) was taken from the Luancheng Experimental Station, Chinese Academy of Sciences (CAS), Shijiazhuang. The soil samples were air dried and sieved (<2 mm stainless steel mesh) before analysis of chemical properties. Soil chemical properties were measured using methods recommended by the Chinese Society of Soil Science (Lu, 1999). Soil pH was measured in a 1:1 soil/water suspension with a combination electrode. Available N was extracted using 2 M KCl solution, available P was extracted

using 0.5 M $NaHCO_3$ and available K was extracted using neutral 1 M NH_4OAc . Cation exchange capacity (CEC) was measured using the method of displacing exchangeable cations on soil particles with NH_4^+ followed by NH_4^+ determination. The soil was supplied with three forms of K fertilizers: KNO_3 (N), KCl (C) and K_2SO_4 (S), and at four levels: CK (0 K), K1 (55 mg K kg^{-1} soil), K2 (110 mg K kg^{-1} soil) and K3 (166 mg K kg^{-1} soil). Thus, altogether, there were 12 treatments. $CdCl_2$ was added to all the treatments at a uniform level equivalent to 15 mg Cd kg^{-1} soil, and there was uniform application of N–P fertilizer at amounts equal to 200 mg N kg^{-1} soil (added as urea) and 133 mg P_2O_5 kg^{-1} soil (added as $CaHPO_4$). Each treatment had four replicates.

2.2. Plant culture

The treated soils were mixed thoroughly and taken into plastic pots (1 kg/pot) and saturated with deionized water. Soil was allowed to equilibrate in the greenhouse for 1 week before sowing the seeds. Four germinated seeds of two cultivars of spring wheat (*Triticum aestivum*, L.), Brookton and Krichauff (from The University of Adelaide, Australia), were planted in each pot. The pots were randomly arranged in a greenhouse and rearranged several times during the growth period. When the seedlings had grown to about 3 cm, they were thinned to three per pot. The seedlings were irrigated with deionized water every 3 days, maintaining the soil moisture content at 15% (w/w) by weighing. The growth temperature was 25 °C on average during 14/10 h light/dark cycles. After 7 weeks, the plants were harvested.

2.3. Plant analysis

After harvest, the seedlings were separated into shoots and roots and rinsed thoroughly with deionized water, and the fresh weights were determined. The samples were then oven dried at 70 °C for 48 h, and the dry weight (DW) of shoots and roots were recorded. Dried plant samples were finely ground in a stainless steel miller.

Subsamples (0.25 g) of finely ground plant materials were digested at 160 °C in 5 ml high-purity mixed acid ($HNO_3/HClO_4 = 6:1$). Reference material (GBW07605) was used for quality control of acid digestion and instrument performance. The digest was diluted to 50 ml using high-purity water, and the concentration of Cd in the digest was determined by inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7500a, USA).

Table 1
Selected chemical properties of the soil used in the pot experiment

pH	OM (%)	Available N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	CEC (cmol/kg (+))	Total Zn (mg kg^{-1})	Total Cd (mg kg^{-1})
7.7	1.4	80.0	24.1	198.7	10.0	176.6	0.1

Table 2

Shoot biomass of spring wheat plants grown in pot culture with different forms and levels of K-fertilizers (g)

Cultivar	Form	Levels of potassium addition (mg kg ⁻¹)			
		0	55	110	166
Brookton	KCl		2.4 ± 0.2	2.4 ± 0.1	2.2 ± 0.1
	KNO ₃	2.6 ± 0.0	3.0 ± 0.5	2.9 ± 0.1	2.5 ± 0.1
	K ₂ SO ₄		2.1 ± 0.0	2.3 ± 0.1	2.2 ± 0.1
Krichauff	KCl		2.4 ± 0.1	2.2 ± 0.2	2.0 ± 0.1
	KNO ₃	2.8 ± 0.2	2.1 ± 0.1	2.5 ± 0.1	2.5 ± 0.2
	K ₂ SO ₄		2.1 ± 0.1	2.4 ± 0.1	2.1 ± 0.0

Analysis of variance

K-form (<i>F</i>)	<i>P</i> < .001
K-level (<i>L</i>)	<i>P</i> < .001
Cultivar (<i>C</i>)	NS
<i>F</i> * <i>L</i>	<i>P</i> = .048
<i>F</i> * <i>C</i>	NS
<i>L</i> * <i>C</i>	<i>P</i> = .018
<i>F</i> * <i>L</i> * <i>C</i>	NS

2.4. Statistical analysis

All data were subjected to the analysis of variance (ANOVA) using commercially available GENSTAT (6th ed., NAG, England).

3. Results

3.1. Plant dry weights

Increasing the application of K fertilizer as KCl and K₂SO₄ significantly reduced the dry weights of plant shoots and roots in both cultivars, but no obvious change was observed in the treatments of KNO₃ (Tables 2 and 3). The dry weights in the treatments KNO₃ were generally higher than those in the other treatments. There was no significant

Table 3

Root biomass of spring wheat plants grown in pot culture with different forms and levels of K-fertilizers (g)

Cultivar	Form	Levels of potassium addition (mg kg ⁻¹)			
		0	55	110	166
Brookton	KCl		0.36 ± 0.04	0.36 ± 0.01	0.32 ± 0.03
	KNO ₃	0.36 ± 0.02	0.40 ± 0.06	0.48 ± 0.02	0.37 ± 0.01
	K ₂ SO ₄		0.30 ± 0.01	0.33 ± 0.03	0.33 ± 0.01
Krichauff	KCl		0.36 ± 0.01	0.33 ± 0.01	0.34 ± 0.02
	KNO ₃	0.42 ± 0.06	0.29 ± 0.02	0.34 ± 0.01	0.36 ± 0.01
	K ₂ SO ₄		0.27 ± 0.02	0.32 ± 0.00	0.32 ± 0.01

Analysis of variance

K-form (<i>F</i>)	<i>P</i> = .008
K-level (<i>L</i>)	<i>P</i> = .002
Cultivar (<i>C</i>)	NS
<i>F</i> * <i>L</i>	NS
<i>F</i> * <i>C</i>	NS
<i>L</i> * <i>C</i>	<i>P</i> = .003
<i>F</i> * <i>L</i> * <i>C</i>	NS

Table 4

K concentrations in shoots of spring wheat plants grown in pot culture with different forms and levels of K-fertilizers (g kg⁻¹)

Cultivar	Form	Levels of potassium addition (mg kg ⁻¹)			
		0	55	110	166
Brookton	KCl		37.4 ± 1.3	37.9 ± 0.5	39.0 ± 0.7
	KNO ₃	30.9 ± 0.20	32.7 ± 0.6	34.4 ± 0.7	36.7 ± 0.5
	K ₂ SO ₄		36.8 ± 0.6	39.4 ± 0.3	41.2 ± 0.5
Krichauff	KCl		39.0 ± 0.5	41.5 ± 0.7	40.6 ± 0.9
	KNO ₃	31.7 ± 0.71	34.0 ± 1.0	32.6 ± 0.5	37.5 ± 1.4
	K ₂ SO ₄		39.8 ± 0.6	40.0 ± 0.3	42.5 ± 1.1

Analysis of variance

K-form (<i>F</i>)	<i>P</i> < .001
K-level (<i>L</i>)	<i>P</i> < .001
Cultivar (<i>C</i>)	<i>P</i> < .001
<i>F</i> * <i>L</i>	<i>P</i> < .001
<i>F</i> * <i>C</i>	<i>P</i> = .066
<i>L</i> * <i>C</i>	NS
<i>F</i> * <i>L</i> * <i>C</i>	NS

difference between the two cultivars in both shoot and root biomass.

3.2. Potassium uptake

Application of K fertilizers significantly increased K concentrations in shoots and roots of both cultivars (*P* < .001). K concentrations in shoots and roots in both cultivars were also affected by the forms of K fertilizers significantly (*P* < .001) (Tables 4 and 5). K concentrations in the treatments of KNO₃ were generally lower than those in the other treatments.

3.3. Cadmium uptake

Cd concentrations in plant roots were different from that of shoots. With the exception of the KCl treatment, the Cd

Table 5

K concentrations in roots of spring wheat plants grown in pot culture with different forms and levels of K-fertilizers (g kg⁻¹)

Cultivar	Form	Levels of potassium addition (mg kg ⁻¹)			
		0	55	110	166
Brookton	KCl		10.1 ± 0.4	11.6 ± 1.1	13.1 ± 0.7
	KNO ₃	8.3 ± 0.4	8.6 ± 0.8	10.6 ± 0.7	10.4 ± 0.5
	K ₂ SO ₄		12.8 ± 0.3	14.8 ± 0.6	14.1 ± 0.6
Krichauff	KCl		10.1 ± 0.2	13.5 ± 0.4	11.7 ± 0.4
	KNO ₃	7.6 ± 0.5	10.2 ± 0.4	9.1 ± 0.5	10.2 ± 0.4
	K ₂ SO ₄		13.5 ± 0.5	13.5 ± 0.4	14.1 ± 0.9

Analysis of variance

K-form (<i>F</i>)	<i>P</i> < .001
K-level (<i>L</i>)	<i>P</i> < .001
Cultivar (<i>C</i>)	NS
<i>F</i> * <i>L</i>	<i>P</i> < .001
<i>F</i> * <i>C</i>	NS
<i>L</i> * <i>C</i>	NS
<i>F</i> * <i>L</i> * <i>C</i>	<i>P</i> = .031

Table 6

Cd concentrations in roots of spring wheat plants grown in pot culture with different forms and levels of K-fertilizers (mg kg^{-1})

Cultivar	Form	Levels of potassium addition (mg kg^{-1})			
		0	55	110	166
Brookton	KCl		194.6 $\pm$ 10.0	220.2 $\pm$ 8.0	275.6 $\pm$ 36.1
	KNO ₃	180.7 $\pm$ 18.7	194.2 $\pm$ 30.7	183.1 $\pm$ 15.2	185.2 $\pm$ 10.4
	K ₂ SO ₄		143.2 $\pm$ 9.6	142.5 $\pm$ 5.1	141.4 $\pm$ 6.3
Krichauff	KCl		158.9 $\pm$ 14.9	207.3 $\pm$ 17.1	138.4 $\pm$ 5.5
	KNO ₃	152.6 $\pm$ 5.1	159.8 $\pm$ 13.0	160.0 $\pm$ 5.2	159.3 $\pm$ 7.2
	K ₂ SO ₄		122.3 $\pm$ 5.6	145.2 $\pm$ 8.2	135.5 $\pm$ 9.6

Analysis of variance

K-form (F)	$P < .001$
K-level (L)	NS
Cultivar (C)	$P < .001$
F*L	$P = .010$
F*C	$P = .022$
L*C	$P = .066$
F*L*C	$P = .015$

concentrations in the roots of both Brookton and Krichauff were decreased marginally in the treatments of K₂SO₄ or unaffected in the treatments of KNO₃ with increasing application K fertilizers (Table 6). Interaction effects between forms and amounts of K fertilizers on Cd concentrations in plant shoots and roots were also significant ($P < .001$).

Cd accumulation in plant shoots of both Brookton and Krichauff increased gradually with increasing application of K fertilizers in the treatments of KCl and K₂SO₄ (Table 7). The concentrations of Cd in shoots increased from 37.5 mg kg^{-1} dry weight (for Brookton) to 81.4 mg kg^{-1} dry weight, and 42.9 mg kg^{-1} dry weight (for Krichauff) to 86.8 mg kg^{-1} dry weight, which were about doubled (Table

Table 7

Cd concentrations in shoots of spring wheat plants grown in pot culture with different forms and levels of K-fertilizers (mg kg^{-1})

Cultivar	Form	Levels of potassium addition (mg kg^{-1})			
		0	55	110	166
Brookton	KCl		68.6 $\pm$ 2.7	66.3 $\pm$ 2.8	71.3 $\pm$ 2.5
	KNO ₃	37.5 $\pm$ 3.5	37.4 $\pm$ 3.5	42.7 $\pm$ 3.1	57.0 $\pm$ 5.5
	K ₂ SO ₄		71.1 $\pm$ 4.5	71.1 $\pm$ 2.4	81.4 $\pm$ 4.0
Krichauff	KCl		69.4 $\pm$ 2.4	70.3 $\pm$ 1.1	74.6 $\pm$ 1.7
	KNO ₃	42.9 $\pm$ 2.2	45.1 $\pm$ 4.4	43.0 $\pm$ 3.0	64.1 $\pm$ 2.1
	K ₂ SO ₄		75.7 $\pm$ 2.1	79.2 $\pm$ 1.9	86.8 $\pm$ 2.5

Analysis of variance

K-form (F)	$P < .001$
K-level (L)	$P < .001$
Cultivar (C)	$P < .001$
F*L	$P < .001$
F*C	NS
L*C	NS
F*L*C	NS

Table 8

Total Cd uptake by spring wheat plants grown in pot culture with different forms and levels of K-fertilizers ($\mu\text{g pot}^{-1}$)

Cultivar	Form	Levels of potassium addition (mg kg^{-1})			
		0	55	110	166
Brookton	KCl		260.8 $\pm$ 7.6	238.0 $\pm$ 9.9	244.2 $\pm$ 22.4
	KNO ₃	176.7 $\pm$ 4.4	203.0 $\pm$ 12.2	208.8 $\pm$ 12.1	213.8 $\pm$ 12.2
	K ₂ SO ₄		192.4 $\pm$ 10.9	210.5 $\pm$ 14.7	229.8 $\pm$ 3.6
Krichauff	KCl		138.2 $\pm$ 1.3	224.7 $\pm$ 7.0	194.4 $\pm$ 10.7
	KNO ₃	169.0 $\pm$ 11.9	221.9 $\pm$ 13.2	157.9 $\pm$ 0.9	218.0 $\pm$ 14.9
	K ₂ SO ₄		182.3 $\pm$ 12.6	234.7 $\pm$ 9.7	231.2 $\pm$ 8.5

Analysis of variance

K-form (F)	$P < .001$
K-level (L)	$P < .001$
Cultivar (C)	NS
F*L	$P < .001$
F*C	NS
L*C	NS
F*L*C	NS

7). In the KNO₃ treatment, however, the Cd concentrations were not significantly affected by increasing the application of K fertilizers except for the highest level (K3). The grand mean of Cd concentrations in the treatments of KNO₃ was 46.2 mg kg^{-1} dry weight, which was much lower than the other treatments (62.6 and 68.2 mg kg^{-1} dry weight from the treatments of KCl and K₂SO₄, respectively).

The two cultivars showed some differences in total Cd uptake. For Brookton, the total Cd uptake in the treatments of K₂SO₄ and KNO₃ were very similar, and were lower than in the treatments of KCl. For Krichauff, however, the total Cd uptake was quite different at lower K levels among the three treatments, but were close at the highest K levels (Table 8). The distribution of Cd in shoots and roots of the two cultivars was significantly different ($P < .001$) between the two cultivars (data not shown), although the total Cd uptake was similar (grand mean: 73.0 and 73.3 mg kg^{-1} for Brookton and Krichauff, respectively). Generally, Cd concentrations were lower in shoots and higher in roots of Brookton than those in Krichauff (Tables 6 and 7).

4. Discussion

Soil contamination with Cd exists in many agricultural soils, and food ingestion is a major pathway of Cd entry to human body. Minimizing the concentrations of Cd in agricultural produce is therefore desirable for the reduction of the human risk of soil Cd contamination. The effect of K fertilizers on plant accumulation of cadmium has rarely been studied in detail in the past. However, it was pointed out by Grant et al. (1999) that the effect of K fertilizers may be due more to the accompanying anions of the salt. Results obtained

in the present study showed that an increase in the application of K fertilizers increased Cd concentrations in both shoots and roots of two wheat cultivars irrespective of the forms of fertilizers (Tables 6 and 7), which suggests that K itself may increase plant uptake of Cd. This is particularly true in the case of KNO_3 treatment, an increase in K addition as KNO_3 significantly increased Cd concentrations in plant shoots (Table 8). However, the mechanisms of K–Cd interactions in plant uptake of Cd need to be elucidated further.

The various potassium forms differed in terms of their effects on Cd accumulation in plants. Some evidence has been reported on Cl^- and SO_4^{2-} increasing Cd uptake by plants (Bingham et al., 1986; Sparrow et al., 1994; McLaughlin et al., 1995). When the level of K addition increased from 0 to 55 mg kg^{-1} soil, the application of KCl and K_2SO_4 resulted in 60–90% increase in Cd concentration in shoots, while the application of KNO_3 only resulted in marginal increase in Cd concentration in shoots. Chloride is well known for forming relatively stable complexes with Cd, CdCl^+ and CdCl_2^0 . Simple stability calculations indicate that the formation of Cd complexes with Cl^- become significant when Cl^- concentration in soil solution rise above about 10 mM (Lindsay, 1979; Norvell et al., 2000), which tends to shift Cd from solid to soil solution, thus enhancing Cd solubility and bioavailability. As Cl^- is a major anion contributing to soil salinity, several studies have now demonstrated that Cd concentrations in wheat grains are positively related to soil salinity (Norvell et al., 2000; Wu et al., 2002). It was also suggested that complexes CdCl_n^{2-n} and CdSO_4^0 were available to plants equivalent to Cd^{2+} (Smolders and McLaughlin, 1996; Smolders et al., 1996; McLaughlin et al., 1998a,b). Sulphate complexes with Cd are not so stable as chloride complexes with Cd (Lindsay, 1979), and the results of both nutrient solution and soil experiments of McLaughlin et al. (1998a,b) showed no significant increasing effects of SO_4^{2-} on Cd uptake by plants although CdSO_4^0 was equivalent to Cd^{2+} . They suggested that SO_4^{2-} would not have the same effect on plant uptake of Cd as Cl^- . Li et al. (1994) reported that Cl^- was much more closely related to Cd accumulation as SO_4^{2-} in sunflower kernels. Our data, however, indicated that the addition of K_2SO_4 and KCl significantly increased Cd concentrations in plants of both cultivars, and that there was no statistically significant difference between KCl and K_2SO_4 . Interestingly, although the shoot Cd concentrations were positively associated with the addition of KCl and K_2SO_4 , the root Cd concentrations were not. Instead, the latter were unaffected or marginally decreased by the addition of K_2SO_4 . In general, the changes in root Cd concentrations were less drastic than in shoot Cd concentrations, which may imply that Cl^- and SO_4^{2-} may affect the root-to-shoot translocation of Cd as well.

Despite the increasing evidence showing the effect of Cl^- and SO_4^{2-} on plant uptake of Cd, there is no evidence to show the uptake of intact Cd complexes with Cl^- and SO_4^{2-} by plant roots either in solution and pot cultures. Further

studies are needed to examine the effects of K-fertilizers on Cd uptake and to investigate the mechanisms involved in the interactions between Cd and Cl^- and SO_4^{2-} in soil–plant systems, which may reveal useful information to guide proper agricultural practices to ensure low Cd accumulation in agricultural produce.

Acknowledgements

This project was supported by the Natural Science Foundation of China (4225002), and the “Recruiting Outstanding Overseas Chinese Scientists” scheme of the Chinese Academy of Sciences, China. We thank Prof K.X. Tian for providing instruction and help during the pot culture, and Dr. D.Y. Chen, Agilent Technologies for ICP-MS analysis.

References

- Basta NT, Raun WR, Gavi F. Wheat grain cadmium under long-term fertilization and continuous winter wheat production. *Better Crops* 1998; 82(19):14–5.
- Bingham FT, Garrison S, Strong JE. The effect of chloride on the availability of cadmium. *J Environ Qual* 1984;13:71–4.
- Bingham FT, Garrison S, Strong JE. The effect of sulfate on the availability of cadmium. *Soil Sci* 1986;141:172–7.
- Cai S, Yue L, Hu Z, Zhong X, Ye Z, Xu H, et al. Cadmium exposure and health effects among residents in an irrigation area with ore dressing wastewater. *Sci Total Environ* 1990;90:67–73.
- Chaney RL, Hornick SB. Accumulation and effects of cadmium on crops. *Cadmium 77. Proc 1st Int Cadmium Conf, San Francisco. London: Metal Bulletin; 1978. p. 125–40.*
- Eriksson JE. Effects of nitrogen-containing fertilizers on solubility and plant uptake of cadmium. *Water Air Soil Pollut* 1990;49:355–68.
- Grant CA, Baily LD. Nitrogen, phosphorus and zinc management effects on grain yield and cadmium concentration in two cultivars of durum wheat. *Can J Plant Sci* 1997;78:63–70.
- Grant CA, Baily LD, Therrien MC. Effect of N, P, and KCl fertilizers on grain yield and Cd concentration of malting barley. *Fertil Res* 1996;45: 153–61.
- Grant CA, Baily LD, McLaughlin MJ, et al. Management factors which influence cadmium concentrations in crops. In: McLaughlin MJ, Singh BR, editors. *Cadmium in soils and plants*. Dordrecht, The Netherlands: Kluwer Academic Publishing; 1999. p. 151–98.
- Li YM, Chaney RL, Schneiter AA. Effect of soil chloride level on cadmium concentration in sunflower kernels. *Plant Soil* 1994;167:275–80.
- Lindsay WL. *Chemical equilibria in soils*. New York: Wiley; 1979.
- Lu RK. *Analytical methods for soils and agricultural chemistry*. Beijing: China Agricultural Science and Technology Press; 1999.
- Mair NA, McLaughlin MJ, Heap M, Butt M, Smart MK. Effects of nitrogen source and calcium lime on soil pH and potato yield, leaf chemical composition, and tuber cadmium concentrations. *J Plant Nutr* 2002; 25(3):523–44.
- McLaughlin MJ, Palmer LT, Tiller KG, Beech TA, Smart MK. Increased soil salinity causes elevated cadmium concentrations in field-grown potato tubers. *J Environ Qual* 1994;23:1013–8.
- McLaughlin MJ, Mair NA, Freeman K, Tiller KG, Williams CMJ, Smart MK. Effect of potassic and phosphatic fertilizer type, fertilizer Cd concentration and zinc rate on cadmium uptake by potatoes. *Fertil Res* 1995;40:63–70.

- McLaughlin MJ, Andrew SJ, Smart MK, Smolders E. Effects of sulfate on cadmium uptake by Swiss chard: I. Effects of complexation and calcium competition in nutrient solutions. *Plant Soil* 1998;202:211–6.
- McLaughlin MJ, Lambrechts RM, Smolders E, Smart MK. Effects of sulfate on cadmium uptake by Swiss chard: II. Effects due to sulfate addition to soil. *Plant Soil* 1998;202:217–22.
- Nordberg GF, Jin T, Kong Q, Ye T, Cai S, Wang Z, et al. Biological monitoring of cadmium exposure and renal effects in a populated group residing in a polluted area in China. *Sci Total Environ* 1997;199:111–4.
- Norvell WA, Wu J, Hopkins DG, Welch RM. Association of cadmium in durum wheat grain with soil chloride and chelate-extractable soil cadmium. *Soil Sci Soc Am J* 2000;64:2162–8.
- Oliver DP, Schultz JE, Tiller KG, Merry RH. The effect of crop rotations and tillage practices on cadmium concentration in wheat grain. *Aust J Agric Res* 1993;44:1221–34.
- Smolders E, McLaughlin MJ. Effect of Cl on Cd uptake by Swiss chard in nutrient solutions. *Plant Soil* 1996;179:57–64.
- Smolders E, McLaughlin MJ, Tiller KG. Influence of chloride on Cd availability to Swiss chard: a resin buffered solution culture system. *Soil Sci Soc Am J* 1996;60:1443–7.
- Sparrow LA, Saladini AA, Jonstone J. Field studies of Cd in potatoes (*Solanum tuberosum* L.): III. Response of cv. Russet Burbank to sources of banded potassium. *Aust J Agric Res* 1994;45:243–9.
- Willaert G, Verloo M. Effects of various nitrogen fertilizers on the chemical and biological activity of major and trace elements in a cadmium contaminated soil. *Pedologie* 1992;43:83–91.
- Wu J, Norvell WA, Hopkins DG, Welch RM. Spatial variability of grain cadmium and soil characteristics in a durum wheat field. *Soil Sci Soc Am J* 2002;66:268–75.
- Zhu YG. Effects of external potassium (K) supply on the uptake of ^{137}Cs by spring wheat (*Triticum aestivum*, cv. Tonic): a large-scale hydroponic study. *J Environ Radioact* 2001;55:303–14.
- Zhu YG, Shaw G, Nisbet AF, Wilkins BT. Effects of external potassium supply on compartmentation and flux characteristics of radiocaesium in intact spring wheat roots. *Ann Bot* 1999;84:639–44.
- Zhu YG, Shaw G, Nisbet AF, Wilkins BT. Effect of potassium supply on the uptake of ^{137}Cs by spring wheat (*Triticum aestivum*, cv. Tonic): a lysimeter study. *Radiat Environ Biophys* 2000;39:283–90.
- Zhu YG, Shaw G, Nisbet AF, Wilkins BT. Effect of potassium supply and plant age on the uptake of radiocaesium (^{137}Cs) by broad bean (*Vicia faba*): interpretation of results from a large-scale hydroponic study. *Environ Exp Bot* 2002;47:173–87.