ELSEVIER

Chemosphere 58 (2005) 475–483

CHEMOSPHERE

www.elsevier.com/locate/chemosphere

Silicon-mediated enhancement of cadmium tolerance in maize (*Zea mays* L.) grown in cadmium contaminated soil

Yongchao Liang [a,b,*], J.W.C. Wong [c], Long Wei [b]

[a] *Institute of Soil and Fertilizer, Ministry of Agriculture Key Laboratory of Plant Nutrition and Nutrient Cycling, Chinese Academy of Agricultural Sciences, Beijing 100081, PR China*

[b] *Department of Plant Nutrition, College of Natural Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing 210095, PR China*

[c] *Department of Biology, Hong Kong Baptist University, Kowloon Tong, Hong Kong*

Received 29 February 2004; received in revised form 3 September 2004; accepted 17 September 2004

Abstract

Pot experiments were performed to study the alleviative effects of exogenous silicon (Si) on cadmium (Cd) phytotoxicity in maize grown in an acid soil experimentally contaminated with Cd. Five treatments were investigated in the first trial consisting of a control (neither Cd nor Si added), Cd added at 20 or 40 mg kg^{-1} Cd without or with Si added at 400 mg kg^{-1} Si. A following-up trial was conducted with almost the same treatments as in the first trial except that Si was incorporated at 50 mg kg^{-1} Si. The results showed that Cd treatment significantly decreased shoot and root dry weight, while addition of Si at both levels significantly enhanced biomass. Addition of Si at 400 mg kg^{-1} Si significantly increased soil pH but decreased soil Cd availability, thus reducing Cd concentration in the shoots and roots and total Cd in the shoots. Moreover, more Cd was found to be in the form of specific adsorbed or Fe–Mn oxides-bound fraction in the Si-amended soil. In contrast, soil pH, available Cd and Cd forms were unaffected by addition of Si at 50 mg kg^{-1} Si, but shoot Cd concentration in the Si-amended Cd treatments significantly decreased at both Cd levels used compared to the non-Si-amended Cd treatments. Total Cd in the shoots and roots was considerably and significantly higher in the Si-amended Cd treatments than in the non-Si-amended Cd treatments. The xylem sap significantly increased but Cd concentration in the xylem sap significantly decreased in the Si-amended Cd treatments compared with the non-Si-amended Cd treatments irrespective of Cd and Si levels used. The results suggest that Si-enhanced tolerance to Cd can be attributed not only to Cd immobilization caused by silicate-induced pH rise in the soils but also to Si-mediated detoxification of Cd in the plants.

Keywords: Cadmium; Cadmium uptake; Dry matter yield; Maize; Silicon

1. Introduction

Contamination of the environment with toxic heavy metals due to anthropogenic activities is one of the major global environmental and human health problems.

* Corresponding author. Address: Department of Plant Nutrition, College of Natural Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing 210095, P.R. China. Tel.: +86 25 84396393.

E-mail address: ycliang@mail.inrrp.com.cn (Y. Liang).

0045-6535/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.chemosphere.2004.09.034

Cadmium (Cd) in the soils, for example, derived mainly from industrial processes, mining activities and repeated agricultural use of sewage sludge and phosphate fertilizers, is extremely toxic to living cells even at low concentrations (Sandalio et al., 2001). Cadmium severely inhibits plant growth and even causes plant death by disturbing the uptake of nutrients (Gussarson et al., 1996; Sandalio et al., 2001) and inhibiting photosynthesis via degradation of chlorophyll (Somashekaraiah et al., 1992; Sandalio et al., 2001) and inactivation of enzymes involved in CO_2 fixation (Greger and Ogren, 1991; De Filippis and Ziegler, 1993). It was also reported that Cd toxicity induced oxidative damage characterized by an accumulation of lipid peroxides and oxidized proteins as a result of the inhibition of the antioxidant systems in plants (Sandalio et al., 2001; Vitória et al., 2001).

Although silicon (Si) has not been considered an essential element for higher plants, it has been well documented that Si can enhance resistance and/or tolerance to Al (Hodson and Evans, 1995; Epstein, 1999; Liang et al., 2001), Mn (Iwasaki et al., 2002a,b; Rogalla and Römheld, 2002) and salt toxicity in plants (Liang, 1999; Yeo et al., 1999; Liang and Ding, 2002; Liang et al., 2003). To date, little information is, however, available on the interactions of Si with Cd (Chen et al., 2000). Addition of 1.7 mM Si had no significant effect on shoot and root dry weight of rice grown hydroponically with 1.0 μM Cd for 6 d, shoot Cd concentration of Si-treated plants, however, was only 51.1% that of Si-deprived ones (Qin and Huang, 1997). Chen et al. (2000) reported that furnace slag was more effective in suppressing Cd uptake by rice and wheat than calcium carbonate or steel sludge. They speculated that the increased pH and available Si arising from the furnace slag contributed to the reduced Cd uptake in plants (Chen et al., 2000). However, convincing evidence is still scant that the reduced Cd uptake is attributable to Si from the furnace slag due to its multi-component. It is generally recognized that pH rise leads to a reduction in Cd availability via Cd immobilization when sodium metasilicate, slag and/or alkaline biosolid are used as Si sources. Nevertheless, mechanisms involved in the Si-enhanced Cd tolerance in plants remain poorly understood. Therefore, pot experiments were performed in this study to investigate the effects of sodium metasilicate incorporated at two contrasting dosages on Cd toxicity of maize (*Zea mays* L.) with respect to plant growth, Cd in the soil, xylem sap and plants grown in an acid soil experimentally contaminated with Cd. The objectives of this paper are (1) to gain better insight into the possible mechanisms involved in Si-mediated detoxification of Cd and (2) to provide both theoretical and practical bases for performing field-scale studies aiming at ameliorating Cd-contaminated soils and environments.

2. Materials and methods

2.1. Experimental conditions and design

First experiment: The soil used for pot experiments was a highly weathered acidic soil (Oxisol) with 4.51 of pH, 12.91 g kg^{-1} of organic matter, 1.40 g kg^{-1} of total N, 0.76 mg kg^{-1} of Olsen-P, 43 mg kg^{-1} of NH_4AC-extractable K and 24.0 g kg^{-1} of NaAC-HAC-extractable Si. The soil was air-dried, crushed to pass a 2 mm sieve and mixed well with 0.25 g kg^{-1} N as urea, 0.15 g kg^{-1} P as KH_2PO_4, and 0.25 g kg^{-1} K as K_2SO_4 and KH_2PO_4. Five treatments with three replicates each were investigated consisting of CK (neither Cd nor Si added), Cd20 and Cd40 (Cd added at 20 and 40 mg kg^{-1} Cd, respectively) without or with Si added at 400 mg kg^{-1} Si (referred to as Si2). Silicon was added as sodium metasilicate ($Na_2SiO_3 \cdot 9H_2O$) and Cd as $CdCl_2 \cdot H_2O$. In order to avoid heterogenous distribution of the Cd added at such a small rate, $CdCl_2 \cdot H_2O$ was dissolved with 50 ml water and then mixed thoroughly with the soil. Finally each 2-l plastic pot filled with 2 kg pretreated soil was watered with tap water daily to keep soil moisture at approximately 90% field water holding capacity for 1 week.

A maize cultivar (*Zea mays* L. cv. Nongda 5108), obtained from China Agricultural University, was used in this experiment. Uniform-sized maize seeds were surface sterilized with 6% H_2O_2 for 10 min, rinsed thoroughly with distilled water, and germinated on moist filter paper for 48 h in an incubator at 25 °C. Five germinated seeds were sown directly into each pot soil. Experiments were conducted in a greenhouse where daily photoperiod was 12 h and the maximum temperature was 35 °C, while the daily minimum temperature at night was adjusted to 25 °C. Tap water (200 ml each time) was used for irrigation when necessary to keep soil moisture at 80% of field water holding capacity. Five days after sowing, each pot was thinned to three seedlings.

Second experiment: This experiment was performed to study the effect of Si on the alleviation of Cd toxicity in maize at such a condition that addition of Si did not significantly change soil pH value. Accordingly, this experiment was conducted under almost the same condition as in the first experiment except that Si was incorporated at 50 mg kg^{-1} Si (referred to as Si1).

2.2. Plant analysis

Fifty-four days (first experiment) and 60 days (second experiment) after sowing plants were harvested and separated into shoots and roots. The shoots were washed thoroughly with tap water and then with distilled water. To remove the ions in the root free space, the roots were washed with 0.5 mM $CaCl_2$ for 30 min and rinsed thoroughly with tap water and finally with distilled water.

The pretreated plant tissues were oven-dried for 72 h at 70 °C and recorded and then ground to pass a 1.0 mm sieve for analyzing Cd concentration. The Cd in plant materials was determined by AAS after dry-ashing. Prior to harvesting, the maize was decapitated in the evening at 4 cm above the shoot base and the decapitated stem was immediately covered with a plastic tube and sealed with cotton for collection of xylem sap. Xylem sap was recorded 18 h after decapitation by weighing the plastic tubes before and after xylem sap collection and used for analysis of Cd by using ICP-MS.

2.3. Soil analysis

Soil samples were collected at harvesting for the analysis of pH, water-soluble (water/soil ratio 2:1) and 0.05 M $CaCl_2$-extractable Cd following the method described by Krishnamurti et al. (2000). Available Si was determined following the method described elsewhere (Liang et al., 1994 and references therein). Cd speciation in the soil was partitioned into four fractions, i.e. exchangeable, specific absorbed, bound to Fe–Mn oxides and bound to organic matter, using the sequential extraction procedure described by Tessier et al. (1979). The extracted Cd was determined by AAS.

2.4. Statistical analysis

All experimental data shown in the tables and figures were examined statistically by analysis of variance. Means of three replicates was subject to Duncan's New Multiple Range Test at 0.05 probability level using SPSS software.

3. Results

3.1. Plant growth and biomass

The treatment with Cd at 20 or 40 mg kg^{-1} Cd significantly reduced shoot and root dry weight (Fig. 1). For example, shoot dry weight in the Cd20 and Cd40 treatments was only 54% and 25% that of the control, respectively (Fig. 1a). However, significantly higher shoot and root dry weight was achieved in the Si-amended Cd treatments compared with the non-Si-amended Cd treatments (Fig. 1). Shoot dry weight was 69% higher in the Si2 + Cd20 treatment than in the Cd20 treatment and 119% higher in the Si2 + Cd40 treatment than in the Cd40 treatment (Fig. 1a). The root dry weight of the Si2 + Cd40 treatment was significantly higher than that

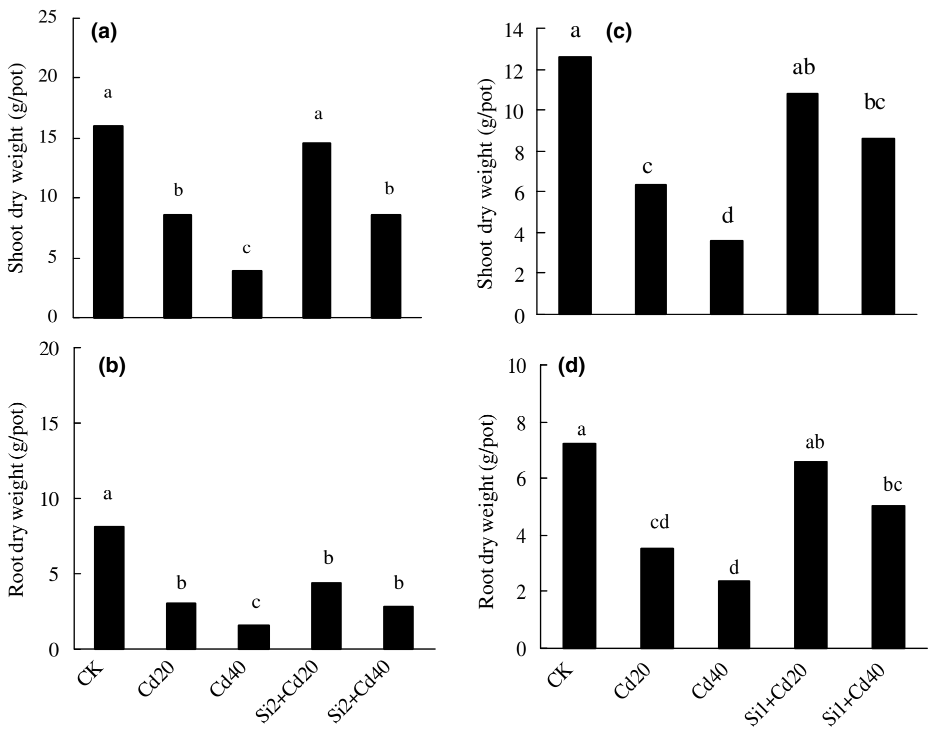

Fig. 1. Shoot and root dry matter yield of maize plants grown on a Cd-contaminated soil amended with either 400 mg kg^{-1} Si (a and b) or 50 mg kg^{-1} Si (c and d). The means marked with the same letter are not significantly different at $p < 0.05$ by Duncan's New Multiple Range Test.

of the Cd40 treatment, while the difference in root dry weight was not statistically significant between the Si2 + Cd20 treatment and the Cd20 treatment (Fig. 1b).

In the second experiment where only 50 mg kg^{-1} Si was added in the Si-amended treatments, added Si still significantly decreased the inhibitory effect of Cd on the growth of maize plants. Shoot dry weight in the Si1 + Cd20 treatment was 72% higher than that in the Cd20 treatment, and 138% higher in the Si1 + Cd40 treatment than in the Cd40 treatment (Fig. 1c). Root dry weight of the Cd20 and the Cd40 treatments was only 49% and 33% that of the control (CK), respectively (Fig. 1d) compared to 91% in the Si1 + Cd20 treatment and 70% in the Si1 + Cd40 treatment. These results suggest that incorporation of Si into Cd-contaminated soils significantly decrease the negative effect of Cd on the growth of maize and enhance Cd tolerance of the plants.

3.2. Cadmium concentration and uptake

Significantly lower shoot and root Cd concentration and total Cd in shoots were noted in the Si-amended Cd treatments than in non-Si-amended Cd treatments in the first experiment (Figs. 2 and 3). For example, shoot Cd concentration of the Si2 + Cd20 treatment was only 35% that of the Cd20 treatment, while that of the Si2 + Cd40 treatment was only 22% that of the Cd40 treatment (Fig. 2a). However, no significant difference in total Cd in roots was observed between Si-amended and non-Si-amended Cd treatments at both Cd levels used (Fig. 3b). Similarly, shoot Cd concentration in the Cd20 treatment was 15% higher than in the Si1 + Cd20 treatment and 36% higher in the Si1 + Cd40 treatment than in the Cd40 treatment (Fig. 2c). Added Si significantly increased total Cd in the shoots and roots at both Cd supply levels (Fig. 3c and d) because of a consequence of significantly higher biomass in the Si-amended Cd treatments (Fig. 1c and d). Total Cd in the shoots and roots was 52% and 260% higher in the Si1 + Cd20 treatment than in the Cd20 treatment, and 65% and 275% higher in the Si1 + Cd40 treatment than in the Cd40 treatment, respectively (Fig. 3c and d).

3.3. Cadmium in xylem sap

The xylem sap flow was significantly reduced in the Cd treatments compared to the control due to the poor root growth in the Cd treatments (Table 1). For example, the xylem sap flow in the Cd20 and Cd40 treatments were, respectively, only 48% and 25% that of the control

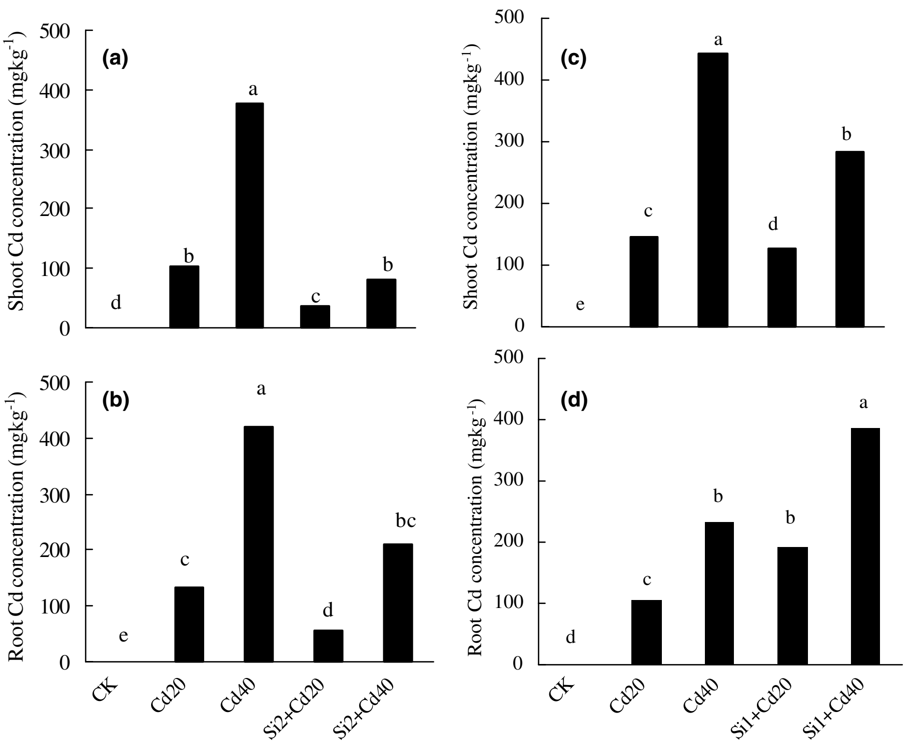

Fig. 2. Cd concentration in the shoots and roots of maize plants grown on a Cd-contaminated soil amended with either 400 mg kg^{-1} Si (a and b) or 50 mg kg^{-1} Si (c and d). The means marked with the same letter are not significantly different at $p < 0.05$ by Duncan's New Multiple Range Test. The value for CK is too small to be detected.

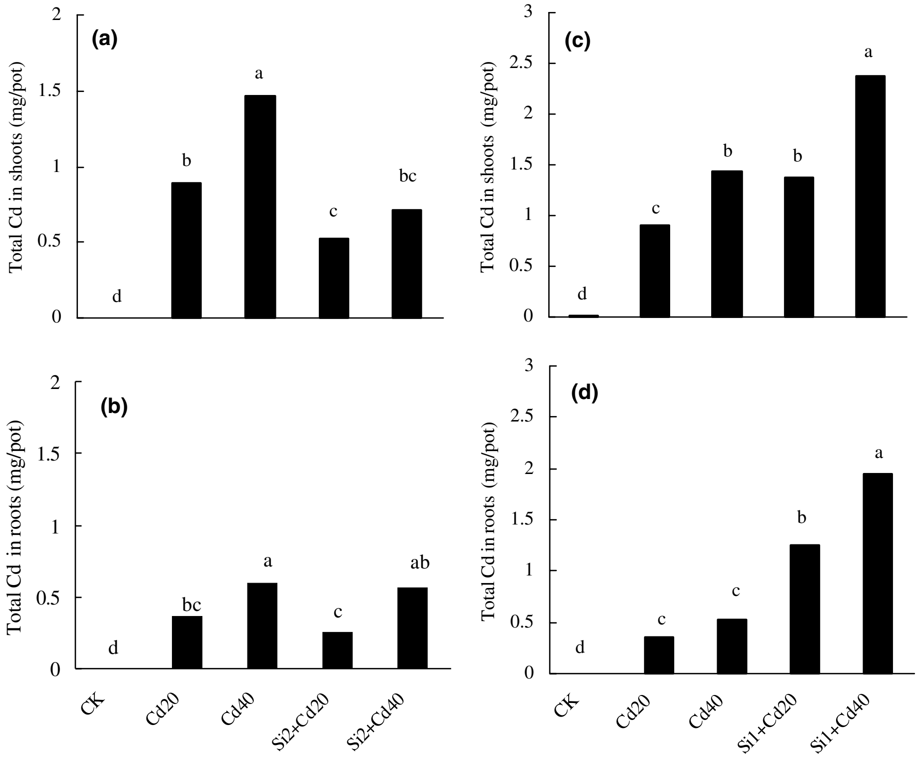

Fig. 3. Total Cd in the shoots and roots of maize plants grown on a Cd-contaminated soil amended with either 400 $mg\,kg^{-1}$ Si (a and b) or 50 $mg\,kg^{-1}$ Si (c and d). The means marked with the same letter are not significantly different at $p < 0.05$ by Duncan's New Multiple Range Test. The value for CK is too small to be detected.

Table 1
Xylem sap flow and Cd concentration in xylem sap of maize grown on a Cd-contaminated soil as affected by exogenous Si

Treatment	Xylem sap flow (ml $18\,h^{-1}\,plant^{-1}$)	Cd concentration (μM)
First experiment		
CK	3.47a	0.5c
Cd20	1.67b	26.5b
Cd40	0.85c	122.1a
Si2 + Cd20	3.23a	6.2c
Si2 + Cd40	2.50b	20.2b
Second experiment		
CK	2.57a	0.2e
Cd20	0.86b	22.8c
Cd40	0.12c	61.5a
Si1 + Cd20	2.40a	13.7d
Si1 + Cd40	0.96b	41.5b

Means followed by the same letters within the same column within the same experiment are not significantly different by Duncan's New Multiple Range Test at $p < 0.05$.

(Table 1). It was, however, 90% higher in the Si2 + Cd20 treatment than in the Cd20 treatment, and 190% higher in the Si2 + Cd40 treatment than in the Cd40 treatment (Table 1). Similar results were achieved in the second experiment where Si was added at 50 $mg\,kg^{-1}$ Si in Si-amended Cd treatments. The xylem sap flow in the Cd20 and Cd40 treatments was, respectively, only 34% and 5% that of the control. In contrast, the xylem sap flow was 1.8-fold higher in the Si1 + Cd20 treatment than in the Cd20 treatment, and 7-fold higher in the Si1 + Cd40 treatment than in the Cd40 treatment (Table 1).

Cadmium concentrations were significantly lower in xylem sap of the Si-amended Cd treatments than in the non-Si-amended Cd treatments (Table 1). The Cd concentration in xylem sap was 77% lower in the Si2 + Cd20 treatment than in the Cd20 treatment and 84% lower in the Si2 + Cd40 treatment than in the Cd40 treatment compared to 39% in the Si1 + Cd20 treatment and 33% in the Si1 + Cd40 treatment (Table 1).

3.4. Soil pH value, and available Cd and Si in the soils

The pH values of postharvest soils significantly increased for the Si-amended Cd treatments in the first

Table 2
Effect of Si on pH value of postharvest Cd-contaminated soils

Treatment	pH value
First experiment	
CK	4.09b
Cd20	4.04b
Cd40	3.91b
Si2 + Cd20	5.24a
Si2 + Cd40	5.10a
Second experiment	
CK	3.97a
Cd20	3.99a
Cd40	3.95a
Si1 + Cd20	4.13a
Si1 + Cd40	4.19a

Means followed by the same letters within the same experiment are not significantly different by Duncan's New Multiple Range Test at $p < 0.05$.

experiment compared with the Cd treatment (Table 2). However, addition of Si did not significantly change soil pH value in the second experiment where only 50 mg kg^{-1} Si was incorporated into the Cd treatments (Table 2). Lower $CaCl_2$-extractable Cd was noted in the Si-amended Cd treatments than in the non-Si-amended Cd treatments in the case of Si added at 400 mg kg^{-1} Si (Fig. 4a). In contrast, no significant difference in $CaCl_2$-extractable Cd was observed between the Si-amended Cd treatments and the non-Si-amended treatments at both Cd levels in the case of Si added at 50 mg kg^{-1} Si (Fig. 4b). Water-soluble Cd in the Cd treatment amended with higher level of Si was drastically reduced at both Cd levels (Fig. 5a), whereas addition of Si at a lower level had no significant effect on water-soluble Cd (Fig. 5b). For instances, water-soluble Cd in the Si2 + Cd20 and Si2 + Cd40 treatments was, respectively, only 8% and 2% that of the corresponding

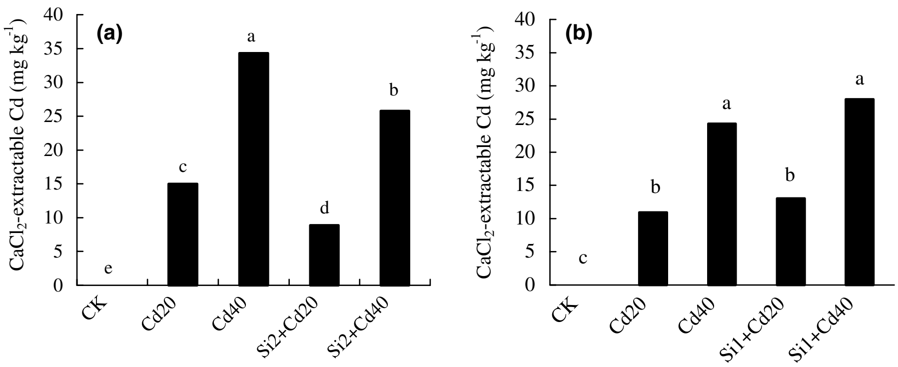

Fig. 4. Effect of Si on 0.05 M $CaCl_2$-extractable Cd of postharvest Cd-contaminated soil in the first experiment (a) and second experiment (b). The means marked with the same letter are not significantly different at $p < 0.05$ by Duncan's New Multiple Range Test. The value for CK is too small to be detected.

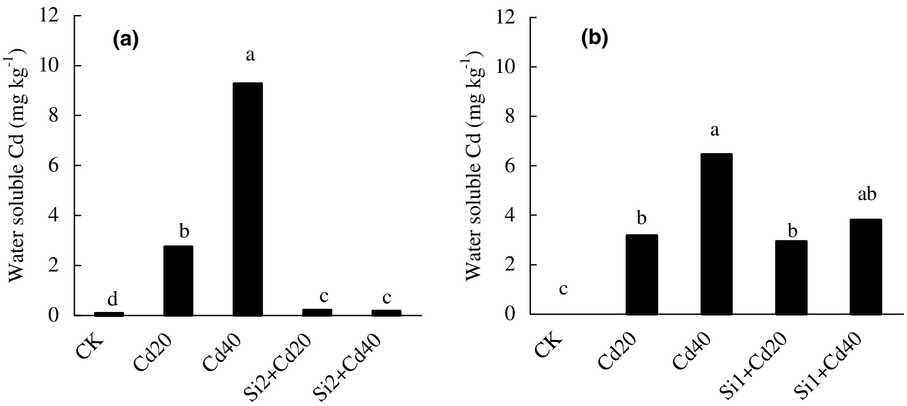

Fig. 5. Effect of Si on water-soluble Cd of postharvest Cd-contaminated soil in the first experiment (a) and second experiment (b). The means marked with the same letter are not significantly different at $p < 0.05$ by Duncan's New Multiple Range Test. The value for CK is too small to be detected.

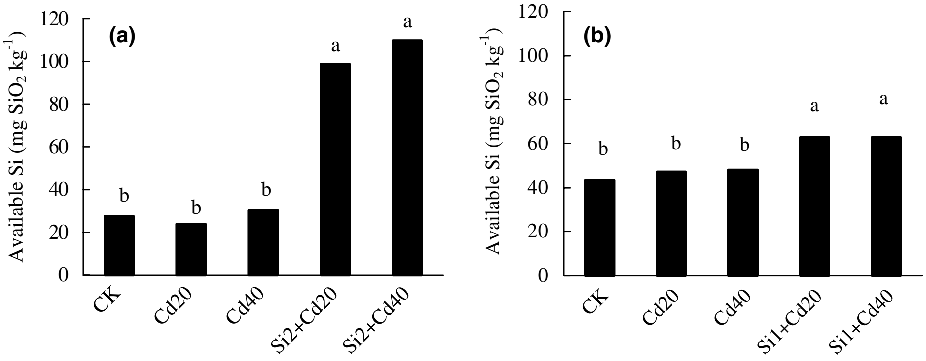

Fig. 6. Effect of Si on available Si concentration of postharvest Cd-contaminated soil in the first experiment (a) and second experiment (b). The means marked with the same letter are not significantly different at $p < 0.05$ by Duncan's New Multiple Range Test.

Table 3
Cadmium fraction (%) in the soil experimentally contaminated with Cd as affected by exogenous Si

Treatment	Exchangeable	Specific adsorbed	Bound to Fe and Mn oxide	Bound to organic matter
First experiment				
CK	nd	nd	nd	nd
Cd20	84.9 ± 1.5a	9.6 ± 0.8b	4.7 ± 0.5b	0.8 ± 0.7b
Cd40	84.4 ± 2.2a	10.1 ± 1.6b	4.8 ± 0.9b	0.7 ± 0.3b
Si2 + Cd20	69.8 ± 0.8c	13.2 ± 1.3a	13.0 ± 1.3a	3.9 ± 1.3a
Si2 + Cd40	72.9 ± 1.0b	12.1 ± 0.3a	12.7 ± 0.9a	2.4 ± 0.4a
Second experiment				
CK	nd	nd	nd	nd
Cd20	91.1 ± 1.8a	8.2 ± 0.6a	0.7 ± 1.1a	nd
Cd40	91.6 ± 5.3a	6.9 ± 4.6a	1.5 ± 0.7a	nd
Si1 + Cd20	86.4 ± 1.6a	10.3 ± 2.0a	3.3 ± 1.6a	nd
Si1 + Cd40	89.9 ± 2.1a	7.4 ± 1.1a	2.7 ± 1.1a	nd

Means followed by the same letters within the same column within the same experiment are not significantly different by Duncan's New Multiple Range Test at $p < 0.05$. nd—not detected (<0.05 mg kg^{-1}).

non-Si-amended Cd treatments (Fig. 5a). The available Si concentrations of the Si-amended Cd treatments in both experiments were significantly increased compared to the Cd treatments (Fig. 6a and b) with the increment being greater in the first experiment where Si was added at a higher level.

3.5. Cadmium fraction in postharvest soil

The results of Cd fractionation showed that exchangeable Cd was predominant form of Cd in the soils of all treatments in both experiments, followed by specific adsorbed Cd extracted with 1.0 M sodium acetate buffer, Cd bound to Fe–Mn oxides and bound to organic matter (Table 3). The addition of 400 mg kg^{-1} Si to the Cd-contaminated soil resulted in a significant reduction in exchangeable Cd at both Cd levels compared with the non-Si-amended Cd treatments, while specific absorbed Cd as well as Cd bound to Fe–Mn oxides and organic matter increased in the first experiment (Table 3). For examples, exchangeable Cd was 18% lower in the Si2 + Cd20 treatment than in the Cd20 treatment and 14% lower in the Si2 + Cd40 treatment than in the Cd40 treatment, whereas Cd bound to Fe–Mn oxides was 1.8-fold higher in the Si2 + Cd20 treatment than in the Cd20 treatment and 1.6-fold higher in the Si2 + Cd40 treatment than in the Cd40 treatment (Table 3). However, addition of 50 mg kg^{-1} Si to the Cd-contaminated soil failed to significantly affect soil Cd fractions as compared to the non-Si-amended Cd treatments in the second experiment (Table 3).

4. Discussion

In the first experiment where as high as 400 mg kg^{-1} Si as sodium metasilicate was added to the Cd treatments, the $CaCl_2$-extractable Cd (Fig. 4a) and especially water-soluble Cd (Fig. 5a) were significantly decreased compared with the non-Si-amended Cd treatments. The reduced availability of Cd (Figs. 4a and 5a) in the Si-amended Cd treatments was a consequence of pH rise (Table 2). The increment of pH in the Si-amended Cd treatments reduced the phytoavailability of Cd, resulting in significantly lower shoot and root Cd concentrations (Fig. 2a and b), and total Cd in the shoots (Fig. 3a). This is partially in line with the reports that reduced uptake of Cd by rice and wheat was a result of the decrease in Cd availability by furnace slag (Chen et al., 2000). This explanation of detoxification via pH-induced Cd immobilization was also supported by the findings in the first experiment that less exchangeable Cd but more specific absorbed and Fe–Mn oxides-bound Cd was observed in the Si-amended than in the non-Si-amended Cd treatments (Table 3). It is suggested that Cd immobilization arising from pH rise by the added metasilicate contribute to the reduced Cd toxicity in maize. However, Cd detoxification in maize observed in the second experiment could not be attributed to pH-induced Cd immobilization in the soil. Supporting evidence are the data showing that no significant differences were noted in soil pH (Table 2), available Cd (Fig. 4b), water-soluble Cd (Fig. 5b) and Cd fractions (Table 3) between the Si-amended and non-Si-amended Cd treatments. Silicate treatment still reduced the inhibitory effect of Cd on plant growth significantly with plant biomass of the Si-amended Cd treatments being substantially higher compared to the non-Si-amended Cd treatments (Fig. 1c and d). Furthermore, total Cd in the shoots and roots were at least 50% and 260% higher in the Si-amended Cd treatments than in the non-Si-amended Cd treatments (Fig. 3c and d) because of higher shoot and root biomass in the Si-amended Cd treatments (Fig. 1c and d). Root Cd concentration was also significantly higher in the Si1 + Cd20 treatment than in the Cd20 treatment (Fig. 2d). However, shoot Cd concentration was greatly lower in the Si1 + Cd40 treatment than in the Cd40 treatment (Fig. 2c), which might be a consequence of "dilution" effect in the Si1 + Cd40 treatment because of its higher biomass. It is thus clear that the Si-amended plants took up more Cd than the non-Si-amended plants (Fig. 3c and d). However, more Cd absorbed by the maize was retained in the roots of the Si-amended plants than in those of the non-Si-amended plants (Fig. 3d), which coincided with the report by Qin and Huang (1997) in rice. The lower Cd concentration in xylem sap in the Si-amended Cd treatments might be also a result of "dilution" effect because of its higher xylem exudation rate (Table 1). The results from this study suggest that the alleviative effect of Cd toxicity observed in the Si-amended Cd treatments was attributed not only to the inactivation or immobilization of Cd caused by pH changes in the rhizosphere soils (e.g. in the first experiment where higher level of Si was incorporated), but also to a Si-mediated mechanism in plants. However, this mechanism involved in Si-mediated Cd detoxification remains poorly understood. Neumann et al. (1997) reported that zinc was co-precipitated as zinc silicate in the leaf epidermal cell wall of *Minuartia verna* and this was an explanation of high zinc tolerance in this plant species. More recent studies with *Cucumber sativus* L. have showed that less Mn (10%) was located in the symplast and more Mn (90%) was bound to the cell wall in the Si-treated plants compared with the non-Si-treated plants (Rogalla and Römheld, 2002). Si-mediated tolerance of Mn in *Cucumber sativus* (Rogalla and Römheld, 2002) and in *Vigna unguiculata* (Iwasaki et al., 2002a,b) was a consequence of stronger binding of Mn to cell walls. This mechanism of Si-induced Mn detoxification may be applicable to Si-mediated Cd tolerance in maize, which, however, needs examining in the further experiments.

Besides the reports showing Si-mediated Mn tolerance (Horst and Marcher, 1978; Horiguchi and Morita, 1987; Iwasaki et al., 2002a,b; Rogalla and Römheld, 2002), more studies reported Si-mediated detoxification of Al in plants (Hodson and Evans, 1995; Epstein, 1999; Liang et al., 2001). Some authors hypothesized that the reduced availability of Al in solutions or growth media via formation of hydroxyaluminosilicate (HAS) species arising from an increase in solution pH by inclusion of Si contributed to Si-mediated detoxification of Al (Hodson and Evans, 1995; Epstein, 1999). However, amelioration was also noted in experiments where HAS formation was minimal, and toxic Al species in the growth solution and the amount of Al uptake by plants were not reduced by Si (Cocker et al., 1998; Liang et al., 2001), suggesting a Si-mediated mechanism in plants. Therefore, it seems to suggest that Si may play an important physiological role in the detoxification of metals within plants.

It should be stressed that the soil used in this study was strongly acidic and there might be some Al toxicity problems. However, no significant difference was observed in water-soluble Al concentrations in postharvest soils, and in shoot and root Al concentrations between any two treatments in the second experiment (data not shown). In contrast, significantly lower water-soluble Al in the postharvest soils and shoot and root Al concentrations were detected in the Si-amended Cd treatments than in the non-Si-amended Cd treatments of the first experiment (data not shown). This was caused by the significantly higher pH in the Si-amended Cd treatments (Table 2). However, we found no Al toxicity symptoms in the control treatment with the roots being white in color and healthy in appearance in both experiments. Roots in the Cd treatments were more brittle, stunted and blackish, which is believed to be the typical symptoms of Cd toxicity rather than of Al toxicity. However, further studies are also needed aiming at understanding the roles of Si in alleviating the combined toxicity of Cd with Al in hydroponics, pot and field experiments at a lower pH because Si can effectively ameliorate Al toxicity in plants (Epstein, 1994; Hodson and Evans, 1995; Cocker et al., 1998).

In conclusion, Si can effectively alleviate the Cd toxicity in maize. The alleviative effect of Si on Cd toxicity can be attributed not only to Cd immobilization and its low phytoavailability arising from pH rise in the Si-amended soil, but also to the Si-mediated Cd detoxification in plants.

Acknowledgment

This research is jointly supported by the grants from National Natural Science Foundation of China (Approved No. 30170536) and from Hong Kong Baptist University (HKBU2043/98M).

References

Chen, H.M., Zheng, C.R., Tu, C., She, Z.G., 2000. Chemical methods and phytoremediation of soil contaminated with heavy metals. Chemosphere 41, 229–234.

Cocker, K.M., Evans, D.E., Hodson, M.J., 1998. The amelioration of aluminium toxicity by silicon in wheat (*Triticum aestivum* L.): malate exudation as evidence for an in planta mechanism. Planta 204, 318–323.

De Filippis, L.F., Ziegler, H., 1993. Effect of sublethal concentrations of zinc, cadmium and mercury on the photosynthetic carbon reduction cycle of *Euglena*. J. Plant Physiol. 142, 167–172.

Epstein, E., 1999. Silicon. Annu. Rev. Plant Physiol. Plant Mol. Biol. 50, 641–664.

Greger, M., Ogren, E., 1991. Direct and indirect effects of Cd^{2+} on photosynthesis in sugar beet (*Beta vulgaris*). Physiol. Plant. 83, 129–135.

Gussarson, M., Asp, H., Adalsteinsson, S., Jensen, P., 1996. Enhancement of cadmium effects on growth and nutrient composition of birch (*Betula pendula*) by buthionine sulphoximine (BSO). J. Exp. Bot. 47, 211–215.

Hodson, M.J., Evans, D.E., 1995. Aluminium/silicon interactions in higher plants. J. Exp. Bot. 46, 161–171.

Horiguchi, T., Morita, S., 1987. Mechanism of manganese toxicity and tolerance of plants. IV. Effect of silicon on alleviation of manganese toxicity of barley. J. Plant Nutr. 10, 299–2310.

Horst, W.J., Marscher, H., 1978. Effect of silicon on manganese tolerance of bean plants (*Phaseolus vulgaris* L.). Plant Soil 50, 287–303.

Iwasaki, K., Maier, P., Fecht, M., Horst, W.J., 2002a. Leaf apoplastic silicon enhances manganese tolerance of cowpea (*Vigna unguiculata*). J. Plant Physiol. 159, 167–173.

Iwasaki, K., Maier, P., Fecht, M., Horst, W.J., 2002b. Effects of silicon supply on apoplastic manganese concentrations in leaves and their relation to manganese tolerance in cowpea (*Vigna unguiculata* (L.) Walp.). Plant Soil 238, 281–288.

Krishnamurti, G.S.R., Smith, L.H., Naidu, R., 2000. Method for assessing plant-available cadmium in soils. Aust. J. Soil Res. 38, 823–836.

Liang, Y.C., 1999. Effects of silicon on enzyme activity, and sodium, potassium and calcium concentration in barley under salt stress. Plant Soil 209, 217–224.

Liang, Y.C., Ding, R.X., 2002. Influence of silicon on microdistribution of mineral ions in roots of salt-stressed barley as associated with salt tolerance in plants. Sci. China (Ser. C) 45, 298–308.

Liang, Y.C., Ma, T.S., Li, F.J., Feng, Y.J., 1994. Silicon availability and response of rice and wheat to silicon in calcareous soils. Commun. Soil Sci. Plant Anal. 25, 2285–2297.

Liang, Y.C., Yang, C.G., Shi, H.H., 2001. Effects of silicon on growth and mineral composition of barley grown under toxic levels of aluminium. J. Plant Nutr. 24, 229–243.

Liang, Y.C., Chen, Q., Liu, Q., Zhang, W.H., Ding, R.X., 2003. Exogenous silicon (Si) increases antioxidant enzyme activity and reduces lipid peroxidation in roots of salt-stressed barley (*Hordeum vulgare* L.). J. Plant Physiol. 160, 1157–1164.

Qin, S.Q., Huang, Q.H., 1997. Effect of Silicon on uptake of cadmium by rice. Environ. Prote. Xinjiang 19, 51–53 (in Chinese).

Rogalla, H., Römheld, V., 2002. Role of leaf apoplast in silicon-mediated manganese tolerance of *Cucumis sativus* L. Plant Cell Environ. 25, 549–555.

Sandalio, L.M., Dalurzo, H.C., Gomez, M., Romero-Puertas, M.C., Del Rio, L.A., 2001. Cadmium-induced changes in the growth and oxidative metabolism of pea plants. J. Exp. Bot. 52, 2115–2126.

Somashekaraiah, B.V., Padmaja, K., Prasad, A.R.K., 1992. Phytotoxicity of cadmium ions on germinating seedlings of mung bean (*Phaseolus vulgaris*): involvement of lipid peroxides in chlorophyll degradation. Physiol. Plant. 85, 85–89.

Tessier, A., Campbell, P.G.C., Bisson, M., 1979. Sequential extraction procedure for the speciation of particulate trace metals. Anal. Chem. 51, 844–851.

Vitória, A.P., Lea, P.J., Azevedo, R.A., 2001. Antioxidant enzymes responses to cadmium in radish tissues. Phytochemistry 57, 701–710.

Yeo, A.R., Flowers, S.A., Rao, G., Welfare, K., Senanayake, N., Flowers, T.J., 1999. Silicon reduces sodium uptake in rice (*Oryza sativa* L.) in saline conditions and this is accounted for by a reduction in the transpirational bypass flow. Plant Cell Environ. 22, 559–565.