Cd and Zn tolerance and accumulation by Sedum jinianum in east China

Xu, L. S., Zhou, S. B., Wu, L. H., Li, N., Cui, L. Q., Luo, Y. M., & Christie, P. (2009). Cd and Zn tolerance and accumulation by Sedum jinianum in east China. International Journal of Phytoremediation, 11, 283-295. DOI: 10.1080/15226510802432744

Published in:
International Journal of Phytoremediation

International Journal of Phytoremediation, 11:283–295, 2009

ISSN: 1522-6514 print / 1549-7879 online
DOI: 10.1080/15226510802432744

Taylor & Francis
Taylor & Francis Group

Cd AND Zn TOLERANCE AND ACCUMULATION BY *SEDUM JINIANUM* IN EAST CHINA

Lisheng Xu,[1,2] Shoubiao Zhou,[3] Longhua Wu,[1] Na Li,[1] Liqiang Cui,[1] Yongming Luo,[1] and Peter Christie[4]

[1]*Key Laboratory of Soil Environment and Pollution Remediation, Institute of Soil Science, Chinese Academy of Sciences; State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Nanjing, China*
[2]*Department of Chemistry and Life Science, Suzhov College, Suzhov, China*
[3]*Key Laboratory of Biological Resources Conservation and Utilization of Anhui Province, College of Life Science, Anhui Normal University, Wuhu, China*
[4]*Agricultural and Environmental Science Department, Queen's University Belfast, Belfast, United Kingdom*

Field survey, hydroponic culture, and pot experiments were carried out to examine and characterize cadmium (Cd) and zinc (Zn) uptake and accumulation by* Sedum jinianum*, a plant species native to China. Shoot Cd and Zn concentrations in* S. jinianum *growing on a lead/Zn mine area reached 103–478 and 4165–8349 mg kg^{-1} (DM), respectively. The shoot Cd concentration increased with the increasing Cd supply, peaking at 5083 mg kg^{-1} (DM) when grown in nutrient at a concentration of 100 μmol L^{-1} for 32 d, and decreased as the solution concentration increased from 200 to 400 μmol L^{-1}. The shoot-to-root ratio of plant Cd concentrations was > 1 when grown in solution Cd concentrations ≤ 200 μmol L^{-1}. Foliar, stem, and root Zn concentrations increased linearly with the increasing Zn level from 1 to 9600 μmol L^{-1}. The Zn concentrations in various plant parts decreased in the order roots > stem > leaves, with maximum concentrations of 19.3, 33.8, and 46.1 g kg^{-1} (DM), respectively, when plants were grown at 9600 μmol Zn L^{-1} for 32 d. Shoot Cd concentrations reached 16.4 and 79.8 mg kg^{-1} (DM) when plants were grown in the pots of soil with Cd levels of 2.4 mg kg^{-1} and 9.2 mg kg^{-1}, respectively. At soil Zn levels of 619 and 4082 mg kg^{-1}, shoot Zn concentrations reached 1560 and 15,558 mg kg^{-1} (DM), respectively. The results indicate that* S. jinianum *is a Cd hyperaccumulator with a high capacity to accumulate Zn in the shoots.

KEY WORDS: *Sedum jinianum*, cadmium (Cd), zinc (Zn), tolerance, accumulation, phytoremediation

INTRODUCTION

Heavy metal contamination of soils is a major environmental problem worldwide and phytoextraction has emerged as a potential *in situ*, cost-effective, and environmentally

Address correspondence to Longhua Wu, Key Laboratory of Soil Environment and Pollution Remediation, Institute of Soil Science, Chinese Academy of Sciences; State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Nanjing 210008, China. E-mail: lhwu@issas.ac.cn

sustainable technique for removing toxic metals from soils (Raskin, Smith, and Salt, 1997; McGrath and Zhao, 2003). Approximately 450 species of metal(loid) hyperaccumulator species belonging to 45 families had been identified up to the year 2000 (Baker *et al*., 2000). Additional species of hyperaccumulators have been reported more recently, for example, *Chromolaena odorata* (L.) King and Robinson (Tanhan *et al*., 2007), *Pteris biaurita* L. (Srivastava, Ma, and Santos, 2006), and *Pityrogramma calomelanos* (Francesconi *et al*., 2002). Recent work in China has been devoted to the hyperaccumulation of zinc (Zn) (Yang *et al*., 2002), cadmium (Cd) (Liu, Shu, and Lan, 2004; Wei *et al*., 2005; Yang *et al*., 2006), arsenic (Wei *et al*., 2002; Chen *et al*., 2003), manganese (Xue *et al*., 2004), and chromium (Zhang *et al*., 2007). The aims of the present study were to survey and analyze *Sedum jinianum* growing at a lead (Pb)/Zn mine area and to examine the growth response and uptake of Cd and Zn by this biennial plant species growing in different concentrations of Cd and Zn in nutrient solution and in soil.

MATERIALS AND METHODS

Zn and Cd Accumulation by *S. jinianum* at a Mine Area

The old Pb/Zn mine selected is located in Zhuji City, Zhejiang Province, eastern China. The local weather is warm and moist with an annual average temperature of 16.2–16.5°C. Seedlings of *S. jinianum* were collected from the Pb/Zn mine area on four occasions, on March 18, April 28, May 31, and June 28, 2006. The ‘Flora in China’ (Wu and Raven, 2001) was named *Sedum jinianum* X. H. Guo (Guo, 1996) as a synonym of *S. bulbiferum* Makino. The plant species we found is different from *S. alfredii* Hance. In fact, *S. alfredii*, *S. bulbiferum*, and *S. jinianum* are three different *Sedum* species. *S. alfredii* is a perennial herb without bulbils in the leaf axils. In contrast, *S. jinianum* is a biennial herb with bulbils in the leaf axils. The full size of the leaf of *S. jinianum* is about 1.5–3.5 cm long and 0.3–0.6 cm wide. The yellow flower of *S. jinianum* has 5 sepals, 5 petals, 10 stamens and 5 carpels. The full size of the leaf of *Sedum alfredii* is about 1–2 cm long and 0.3–0.8 cm wide. The yellow flower of *S. alfredii* has four sepals, four petals, four stamens, and eight carpels (Yang *et al*., 2002).

Hydroponic Culture of *S. jinianum*

Hydroponic culture was established to examine the growth and Zn and Cd tolerance and accumulation by plants growing in different concentrations of Zn or Cd in nutrient solution. The Cd and Zn concentrations in the shoots of seedlings collected in the field were 117 and 5868 mg kg^{-1}, respectively. The average biomass of each seedling was 0.0154 mg (DM). The composition of the nutrient solution was (mmol L^{-1}): $Ca(NO_3)_2$ $4H_2O$ 1.0, KH_2PO_4 0.50, $MgSO_4$ $7H_2O$ 0.50, KCl 0.10, K_2SO_4 0.70, MES 1.0, and KOH 0.5 and (μmol L^{-1}): H_3BO_3 10.0, $MnSO_4$ H_2O 0.50, $ZnSO_47H_2O$ 0.50, $CuSO_45H_2O$ 0.20, $(NH_4)_6Mo_7O_{24}$ 0.01, and iron-Ethylenediaminetetraaceticacid (EDTA) 100. The Cd treatments were control (without the addition of Cd) and 50, 100, 200, and 400 μmol Cd L^{-1} as $Cd(NO_3)_2$. NH_4NO_3 was used to balance the nitrogen supply for all treatments. The Zn treatments were 1.0 (control) and 400, 800, 1600, 3200, 6400, and 9600 μmol Zn L^{-1} as $ZnSO_4$. Seedlings were precultured for 20 d before exposure to the different Cd or Zn treatments. Each container had four plants and each treatment was replicated four times. The nutrient solution was aerated and replaced every 4 d. Plants were grown under glasshouse conditions for 32 d.

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

Property	Low contamination	High contamination
pH (soil:H_2O = 1:2.5)	5.55	6.53
Total N (g kg^{-1})	3.75	2.21
Total P (g kg^{-1})	0.24	0.22
Total K (g kg^{-1})	21.5	22.9
Available N (mg kg^{-1})	200	108
Available P (mg kg^{-1})	5.56	6.70
Available K (mg kg^{-1})	48.7	135
Organic Carbon (g kg^{-1})	25.7	25.1
Total Cd (mg kg^{-1})	2.49	9.28
Total Zn (mg kg^{-1})	619	4082

Another hydroponic culture experiment was conducted at the same time to study the Cd and Zn uptake and accumulation dynamics of *S. jinianum*. The plants were prepared as described earlier and treatments comprised 100 μmol Cd L^{-1} and 800 μmol Zn L^{-1}. The plants were harvested after exposure to the Cd and Zn treatments for 1, 3, 5, 7, 15, 21, and 32 d. Each treatment had three replicates at each harvest time. The nutrient solution was replaced every 2 d and the solution pH was maintained at 5.6. The plant growth conditions were the same as for the first hydroponic culture experiment.

Pot Experiment: Zn and Cd Accumulation by *S. jinianum* from Contaminated Soil

The 0–20-cm surface layer of an alluvial soil was sampled from Fuyang City, Zhejiang Province, eastern China. The soil was air-dried and passed through a 2-mm nylon mesh before use. Selected soil properties analyzed by standard methods (Lu, 2000) are shown in Table 1. Air-dried soil equivalent to 1.5 kg on an oven-dry basis was placed in each pot after fertilizer addition at rates of 100, 50, and 100 mg kg^{-1} of N, P, and K, respectively, as NH_4NO_3, KH_2PO_4, and KCl. Four seedlings of *S. jinianum* were transplanted in each pot and each treatment was replicated four times. Plant growth conditions were the same as described earlier for the nutrient-solution experiments.

Sample Pretreatment and Analysis

The plants grown in the nutrient solution were separated into leaves, stems, and roots and those grown in the soil were separated into shoots and roots. The plants were washed first with tap water and then with deionized water. Roots were immersed in a solution of 20 mmol L^{-1} Na_2-EDTA for 30 min to remove extracellular metals before washing with tap water and deionized water. The washed root, stem, and leaf samples were dried at 80°C for 48 h, then their dry weights were recorded and were ground and digested with HNO_3 and $HClO_4$. Cd and Zn were determined by atomic absorption spectrophotometry (Varian SpectrAA 220 FS, Varian, Palo Alto, CA, USA) (Zhao, McGrath, and Crosland, 1994). Blanks and plant standard reference materials were included in each batch for quality control.

Table 2 Cd and Zn concentrations in the shoots and roots of *Sedum jinianum* growing in the Pb/Zn mine area at different times of year

	Cd concentration (mg kg −1)		Zn concentration (mg kg −1)	
Date	Shoot	Root	Shoot	Root
March 18	117 ± 29^{b}	276 ± 122^{ab}	5868 ± 3436^{ab}	8050 ± 4269^{a}
April 28	103 ± 9^{b}	399 ± 52^{a}	4165 ± 356^{b}	6148 ± 1069^{a}
May 31	113 ± 34^{b}	283 ± 127^{ab}	7640 ± 5378^{ab}	10009 ± 4670^{a}
June 28	478 ± 44^{a}	132 ± 87^{b}	8349 ± 255^{a}	7596 ± 3215^{a}

Values are means ± SE, $n = 6$. Values followed by different letters on the same date are significantly different at $P < 0.05$.

Statistical Analysis

Analysis of variance was performed on each measured variable and means and standard errors (SE) were calculated. The least significant difference ($P < 0.05$) was used for multiple comparisons among treatment means. Descriptive statistics were calculated using the SPSS v.13.0 software package and Microsoft Excel.

RESULTS

Cd and Zn Concentrations in *S. jinianum* Growing in the Mine Area

From March to June 2006, Cd concentrations in *S. jinianum* shoots and roots varied from 103 to 478 and from 132 to 399 mg kg^{-1}, respectively (Table 2). Shoot and root Zn concentrations were 4165–8349 and 6148–10,009 mg kg^{-1}, respectively (Table 2). The soil from the mine area had total Cd and Zn concentrations of 64 and 9894 mg kg^{-1}, respectively. Cd and Zn concentrations in plant shoots and roots did not vary significantly ($P > 0.05$) during this period except for shoot Cd concentrations, which were significantly higher ($P < 0.05$) at the last collection time on June 28, 2006.

Plant Growth and Cd and Zn Uptake at Different Cd and Zn Concentrations in Nutrient Solution

Plant growth appeared normal at solution Cd concentrations of 0–200 μmol L^{-1}. Toxicity symptoms with necrosis and browning of root tips were found after 7 d of treatment with 400 μmol L^{-1} Cd and the older leaves began to fall off after 11 d in this treatment. The dry weights of leaves, stems, and roots increased when the plants were grown in solution with Cd concentrations of ≤ 100 μmol L^{-1}, then reduced with increasing Cd concentration from 200 to 400 μmol L^{-1} (Table 3). The biomass of each seedling at transplanting did not influence the final dry weight because the average seedling biomass was only 0.0154 mg (DM) and the Cd and Zn concentrations in the seedling shoots at transplanting did not influence the final Cd and Zn concentrations in the plants. Root length increased at a Cd concentration of 100 μmol L^{-1} (Table 3). Shoot height decreased gradually with increasing solution Cd concentration from 0 to 400 μmol L^{-1} (Table 3). However, the number of branches increased when the plants were grown at Cd concentrations from 0 to 400 μmol L^{-1}, indicating that *S. jinianum* has a very high Cd tolerance.

Table 3 Growth response of *S. jinianum* to different Cd concentrations in nutrient solution

Solution Cd (μmol L^{-1})	Dry weight (g $plant^{-1}$) Leaf	Stem	Root	Plant height (cm)	Root length (cm)
0	0.162 ± 0.015^{b}	0.082 ± 0.023^{ab}	0.029 ± 0.005^{a}	14.5 ± 1.01^{a}	6.90 ± 0.28^{a}
50	0.233 ± 0.017^{a}	0.098 ± 0.009^{a}	0.017 ± 0.005^{a}	12.0 ± 1.28^{ab}	7.08 ± 0.18^{a}
100	0.239 ± 0.021^{a}	0.104 ± 0.018^{ab}	0.021 ± 0.003^{a}	9.77 ± 0.613^{b}	7.84 ± 0.51^{b}
200	0.165 ± 0.011^{b}	0.057 ± 0.014^{b}	0.012 ± 0.000^{ab}	7.00 ± 0.467^{c}	7.04 ± 0.31^{a}
400	0.041 ± 0.013^{c}	0.018 ± 0.003^{c}	0.010 ± 0.002^{b}	6.50 ± 0.385^{c}	6.56 ± 0.12^{a}

Values are means $\pm$ SE, $n = 4$. Values followed by different letters in the same column are significantly different at $P < 0.05$.

At external Zn concentrations ≤ 1600 μmol L^{-1}, the plants appeared to grow normally with no visual symptoms of toxicity. The roots turned black but the shoots remained alive when the plants were grown at an external Zn concentration of 6400 μmol L^{-1}. Under these conditions, wilting of the leaves and putrescence of the root tips were observed. Dry weights of leaves, stems, and roots increased with increasing Zn concentration and peaked at 1600 μmol L^{-1}. Shoot height and root length increased when the plants were grown at Zn concentrations from 1.0 to 1600 μmol L^{-1} and then decreased with the increasing Zn supply from 3200 to 9600 μmol L^{-1} (Table 4). These results indicate that *S. jinianum* can also tolerate high Zn concentrations in the nutrient solution.

Shoot Cd concentrations increased markedly with increasing solution Cd concentration, peaking at 100 μmol L^{-1} and then decreasing with increasing external Cd concentration from 200 to 400 μmol L^{-1}. Root Cd concentration increased when solution Cd concentration increased from 0 to 400 μmol L^{-1}. At an external Cd concentration of 50–200 μmol L^{-1}, shoot Cd concentrations were higher than root Cd concentrations (Table 5) and the stems showed the highest Cd concentrations (Table 5). Biological transfer coefficients (the ratio of shoot-to-root Cd concentration, biological transfer coefficients [BTC]) were 1.39–3.14 when the plants were grown at external Cd concentrations of

Table 4 Growth response of *S. jinianum* to different Zn concentrations in nutrient solution

Zn treatment (μmol L^{-1})	Dry weight (g $plant^{-1}$) Leaf	Stem	Root	Plant height (cm)	Root length (cm)
1	0.390 ± 0.109^{d}	0.251 ± 0.099^{c}	0.035 ± 0.012^{e}	16.4 ± 2.1^{cd}	7.89 ± 0.57^{d}
400	0.816 ± 0.060^{bc}	0.565 ± 0.075^{b}	0.167 ± 0.014^{bc}	22.6 ± 1.7^{ab}	14.3 ± 0.8^{ab}
800	0.764 ± 0.133^{bcd}	0.650 ± 0.107^{b}	0.193 ± 0.029^{b}	23.9 ± 1.2^{a}	14.7 ± 0.7^{a}
1600	1.34 ± 0.19^{a}	0.940 ± 0.085^{a}	0.265 ± 0.033^{a}	24.2 ± 1.2^{a}	15.1 ± 0.8^{a}
3200	0.938 ± 0.146^{b}	0.599 ± 0.076^{b}	0.172 ± 0.019^{bc}	19.7 ± 1.3^{bc}	13.0 ± 0.4^{bc}
4800	0.778 ± 0.154^{bc}	0.478 ± 0.085^{bc}	0.157 ± 0.024^{bcd}	17.6 ± 1.6^{cd}	11.9 ± 0.4^{c}
6400	0.490 ± 0.016^{cd}	0.280 ± 0.036^{c}	0.094 ± 0.006^{de}	14.2 ± 1.2^{d}	11.8 ± 0.3^{c}
9600	0.542 ± 0.102^{cd}	0.308 ± 0.049^{c}	0.107 ± 0.023^{cd}	14.7 ± 0.4^{d}	11.4 ± 0.5^{c}

Values are means $\pm$ SE, $n = 4$. Values followed by different letters in the same column are significantly different at $P < 0.05$.

Table 5 Cd concentration, uptake, and BTCs of *Sedum jinianum* grown at different Cd levels in nutrient solution

Solution Cd (μmol L-1)	Cd concentration (mg kg^{-1})				Cd uptake (μg plant^{-1})		BTC
	Leaf	Stem	Root	Shoot	Shoot	Root	
0	3.97 ± 0.44^{b}	17.7 ± 8.1^{c}	41.7 ± 4.9^{c}	9.23 ± 2.70^{c}	2.38 ± 0.95^{d}	0.76 ± 0.08^{c}	0.222
50	474 ± 54.0^{b}	3235 ± 768^{b}	937 ± 175^{c}	1711 ± 369^{b}	580 ± 163^{bc}	17.4 ± 8.12^{bc}	1.83
100	2169 ± 408^{a}	8240 ± 528^{a}	1617 ± 133^{bc}	5085 ± 179^{a}	1756 ± 208^{a}	34.6 ± 6.40^{ab}	3.14
200	2884 ± 503^{a}	8957 ± 1837^{a}	3608 ± 1041^{b}	5004 ± 1091^{a}	1126 ± 301^{b}	44.7 ± 12.9^{a}	1.39
400	482 ± 135^{b}	2747 ± 491^{bc}	6117 ± 1333^{a}	1172 ± 101^{bc}	22.8 ± 3.38^{cd}	19.3 ± 2.37^{bc}	0.192

Values are means ± SE, $n = 4$. Values followed by different letters in the same column are significantly different at $P < 0.05$.

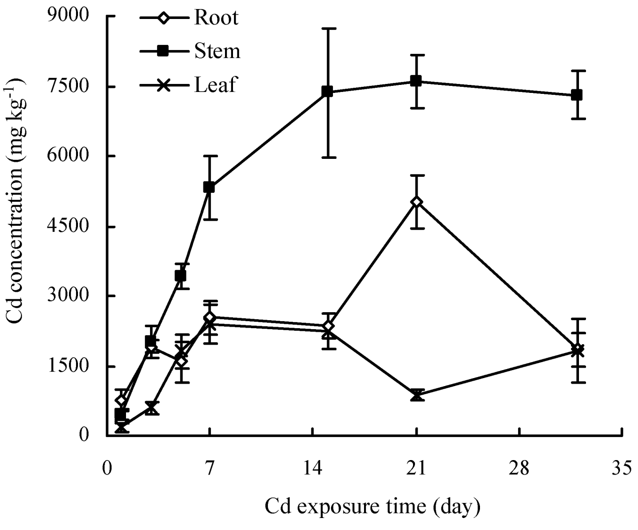

Figure 1 Dynamics of Cd uptake in the leaves, stems, and roots of *Sedum jinianum* with Cd exposure time at an external Cd concentration of 100 μmol L^{-1} in nutrient solution. All the data are means of four replicates and the error bars depict the SE.

50–200 μmol L^{-1} (Table 5). Compared with the control, the increases in foliar and stem Cd concentrations were statistically significant ($P < 0.05$) at solution Cd concentrations of 100–200 μmol L^{-1} (Table 5). Cd uptake by the shoots increased linearly with external Cd concentration, peaking at an external concentration of 100 μmol Cd L^{-1} and then decreasing with a further increase in solution Cd concentration from 100 to 400 μmol L^{-1}. Maximum shoot Cd accumulation was 1765 μg plant^{-1} when the plants were grown at a solution Cd concentration of 100 μmol L^{-1} (Table 5). The amount of Cd accumulated in the roots was small (only 0.76–44.7 μg plant $^{-1}$) at external Cd concentrations from 0 to 400 μmol L^{-1} (Table 5). At an external Cd concentration of 100 μmol L^{-1}, stem Cd concentrations increased quickly within 21 d of treatment, then reached a plateau from 21 to 32 d. Maximum stem Cd concentration was 7593 mg kg^{-1} (DW) when the plants were grown with 100 μmol L^{-1} at 21 d (Figure 1). These results imply that *S. jinianum* has a marked capacity to hyperaccumulate Cd in the shoots and, therefore, may be a potential candidate species for phytoextraction of Cd from contaminated soils.

Foliar, stem, and root Zn concentrations increased linearly with the increasing solution Zn concentration (Table 6). The Zn concentrations in various parts of the plants decreased in the order of roots > stem > leaves. Maximum foliar, stem, and root Zn concentrations were 19.3, 33.8, and 46.1 g kg^{-1} (DM), respectively, when the plants were grown in nutrient solution with 9600 μmol Zn L^{-1} for 32 d (Table 6). The BTCs of Zn were 0.501–0.999 when the plants were grown in solution with Zn concentrations of 1.0–9600 μmol L^{-1} (Table 6). Shoot Zn uptake increased linearly with the increasing Zn supply, peaking at a solution Zn concentration of 1600 μmol L^{-1} and then decreasing with further increase in external Zn concentration from 3200 to 9600 μmol L^{-1} (Table 6). At an external Zn concentration of 800 μmol L^{-1}, stem and foliar Zn concentrations increased slightly within 21 d of treatment, then increased sharply from days 21 to 32 of treatment. Root Zn concentrations increased slowly during the first week of treatment, then increased sharply between days 7 and 21 and reached a plateau between days 21 and 32. The maximum stem and foliar

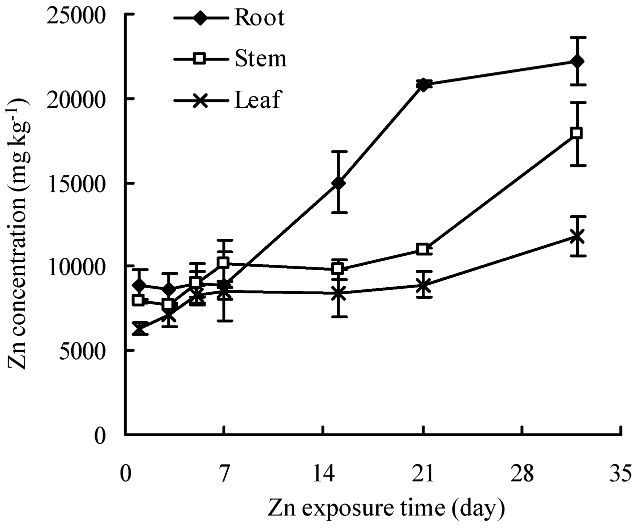

Figure 2 Dynamics of Zn uptake by the leaves, stems, and roots of *Sedum jinianum* with Zn exposure time at an external Zn concentration of 800 μmol L^{-1} in nutrient solution. All the data are means of four replicates and the error bars depict the SE.

Zn concentrations were 17870 and 11779 mg kg^{-1} (DW), respectively, at an external Zn concentration of 800 μmol L^{-1} for 32 d (Figure 2).

S. jinianum Growth and Cd and Zn Uptake in Contaminated Soil

S. jinianum exhibited normal growth in soil under both experimental treatments. At a soil Cd concentration of 2.4 mg kg^{-1}, foliar and root Cd concentrations reached 16.4 and 54.4 mg kg^{-1} (DM), respectively (Figure 3A). At a soil Cd concentration of 9.2 mg kg^{-1}, foliar and root Cd concentrations reached 79.8 and 68.8 mg kg^{-1} (DM), respectively (Figure 3A). At soil Cd concentrations of 2.4 and 9.2 mg kg^{-1}, biological concentration factors (ratio of the foliar-to-total soil Cd concentration) were 6.8 and 8.7, respectively. At a soil Zn concentration of 619 mg kg^{-1}, foliar and root Zn concentrations reached 1560 and 4823 mg kg^{-1} (DW), respectively (Figure 3B). At a soil Zn concentration of 4082 mg kg^{-1}, foliar and root Zn concentrations reached 15,558 and 42,689 mg kg^{-1} (DW), respectively (Figure 3B), the Zn biological concentration factors (the ratio of foliar-to-soil Zn concentration) were 2.5 and 3.8, respectively. These results indicate that *S. jinianum* has the capacity to hyperaccumulate Cd and accumulate high concentrations of Zn in the shoots.

DISCUSSION

Cadmium hyperaccumulators are defined as plants that are capable of accumulating more than 100 mg Cd kg^{-1} in the shoots (Baker *et al.*, 2000). The original criterion suggested for Zn hyperaccumulation was 10,000 mg Zn kg^{-1} in the shoot dry matter (Baker and Brooks, 1989). Until now, only a small number of Cd and Zn hyperaccumulators have been identified, including *Thlaspi caerulescens*, *Arabidopsis* halleri, and *Sedum alfredii* Hance (Brown *et al.*, 1995bb; Lombi *et al.*, 2000; Küpper *et al.*, 2000; Yang *et al.*, 2004). In

Table 6 Zn concentration, uptake, and BTCs of *S. jinianum* grown in nutrient solution with different Zn concentrations

Solution Zn (μmol L-1)	Zn concentration (g kg^{-1})				Zn uptake (mg $plant^{-1}$)		BTC
	Leaf	Stem	Root	Shoot	Shoot	Root	
1	0.49 ± 0.09^{d}	1.23 ± 0.38^{e}	0.72 ± 0.13^{e}	0.72 ± 0.20^{f}	0.45 ± 0.07^{d}	0.03 ± 0.01^{d}	0.999
400	12.9 ± 2.2^{b}	13.3 ± 0.2^{d}	24.1 ± 5.6^{cd}	13.1 ± 1.6^{e}	17.7 ± 0.68^{c}	3.95 ± 0.76^{c}	0.543
800	14.3 ± 0.3^{bc}	17.2 ± 2.0^{cd}	22.4 ± 5.8^{d}	15.8 ± 0.9^{ce}	22.2 ± 3.61^{c}	3.97 ± 0.59^{c}	0.705
1600	15.8 ± 1.7^{ab}	21.3 ± 2.7^{c}	33.9 ± 2.5^{bc}	18.5 ± 0.5^{c}	42.1 ± 4.43^{a}	9.07 ± 1.54^{a}	0.548
3200	17.6 ± 2.0^{ac}	27.1 ± 1.8^{b}	35.5 ± 3.0^{ab}	22.4 ± 1.5^{bd}	33.7 ± 2.46^{ab}	6.15 ± 1.00^{bc}	0.631
4800	15.0 ± 0.9^{bc}	28.4 ± 2.5^{ab}	43.3 ± 2.1^{ab}	21.7 ± 1.7^{bc}	26.8 ± 4.70^{bc}	6.69 ± 0.74^{ab}	0.501
6400	15.8 ± 0.2^{abc}	28.4 ± 0.4^{ab}	43.5 ± 3.6^{ab}	22.1 ± 0.3^{b}	17.0 ± 0.82^{c}	4.04 ± 0.07^{c}	0.507
9600	19.3 ± 1.6^{a}	33.8 ± 0.2^{a}	46.1 ± 2.4^{a}	26.5 ± 1.5^{a}	23.0 ± 4.96^{c}	4.83 ± 0.88^{bc}	0.576

Values are means ± SE, $n = 4$. Values followed by different letters in the same column are significantly different at $P < 0.05$.

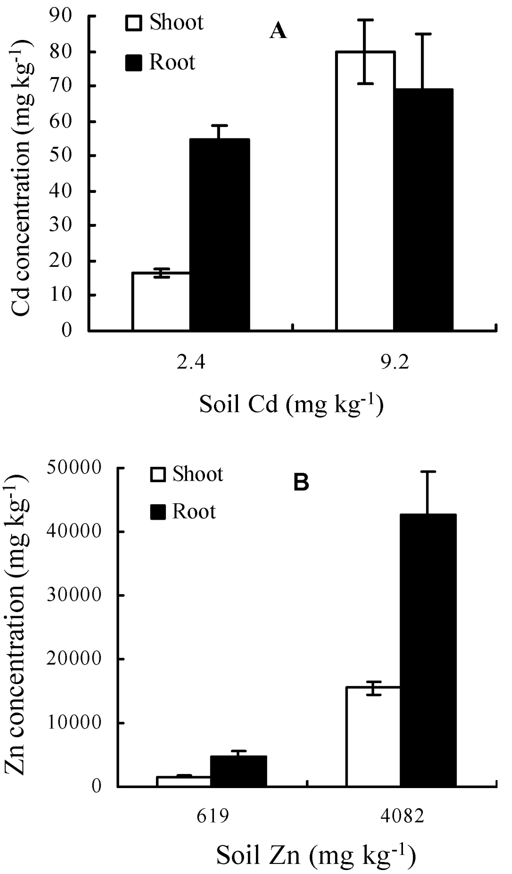

Figure 3 Cd (**A**) and Zn (**B**) concentrations in the shoots and roots of *Sedum jinianum* grown at different soil total Cd concentrations. All the data are means of four replicates and the error bars depict the SE.

the present study, Cd concentrations in *S. jinianum* shoots varied from 103 to 478 mg kg^{-1} at the Pb/Zn mine area at different growth stages and the biomass of *S. jinianum* leaves, stems, and roots showed no decrease in solution culture, even at Cd concentrations up to 100 μmol L^{-1}. This indicates that *S. jinianum* can tolerate and accumulate high concentrations of Cd. However, the plants grew slowly and remained small, as reported for *T. caerulescens* (Robinson *et al.*, 1998; Ebbs and Kochian, 1997, 1998). Yang *et al.* (2004) reported that *S. alfredii* Hance leaves had higher Cd concentrations than did the stems. The present results indicate that *S. jinianum* accumulated more Cd in the stems than in the leaves (Table 5). This suggests that differences in the distribution of Cd occur in members of the family Crassulaceae. The dynamics of Cd uptake indicate that Cd accumulation in the stems, leaves, and roots were different when the plants were grown with 100 μmol Cd L^{-1} in the external solution. The Cd uptake kinetics indicate that a high-affinity Cd transporter system may exist in the root cell plasma membranes of *Thlaspi caerulescens* (Lombi *et al.*, 2001). Elucidation of the biochemical and molecular mechanisms of Cd homeostasis in the stems, leaves, and roots of *S. jinianum* requires further study.

About 18 species of Zn hyperaccumulators were identified up to 2000 (Reeves and Baker, 2000) and the number of reported Zn hyperaccumulators, for example, *S. alfredii* Hance (Yang *et al.*, 2002), has increased recently. They have been found mainly in colonized areas with high Zn, Cd, and Pb present in soil due to historical mining activities and the subsequent contamination of the topsoil with mine spoil rich in heavy metals, especially in parts of Europe and Australia (Reeves and Baker, 2000; Baker *et al.*, 2000). The present study indicates that *S. jinianum* can tolerate Zn concentrations up to 1600 μmol L^{-1} in nutrient solution without a reduction in dry matter yield, which is similar to published results for *T. caerulencens* (Brown *et al.*, 1995bb), *A. halleri* (Bert *et al.*, 2000; Zhao *et al.*, 2000), and *S. alfredii* Hance (Yang *et al.*, 2006). The Zn concentrations in the leaves, stems, and roots increased linearly with increasing Zn concentration in the nutrient solution from 1.0 to 9600 μmol L^{-1}, whereas Zn accumulation patterns in shoots of *T. caerulencens* and *A. halleri* increased linearly with increasing Zn levels up to 1000 μmol L^{-1} (Brown *et al.*, 1995aa; Zhao *et al.*, 2000), and in *S. alfredii* Hance increased linearly with Zn concentrations up to 500 μmol L^{-1} (Yang *et al.*, 2006). This suggests that *S. jinianum* may also tolerate high Zn concentrations in nutrient solution. However, the BTCs for Zn were less than 1. The bioaccumulation factors for Zn and Cd were more than 1 when the plants were grown in Zn- and Cd-contaminated soil, indicating that *S. jinianum* is a Cd hyperaccumulator that also has a high capacity to accumulate Zn in the shoots. As far as we know, this is the first report of Cd hyperaccumulation by *S. jinianum*. Therefore, this plant species can be added to the list of hyperaccumulators that may prove useful for future studies on the mechanisms of Cd hyperaccumulation by higher plants and on the phytoremediation of soils contaminated with Cd and Zn.

ACKNOWLEDGEMENTS

The National Natural Science Foundation of China (grant 40621001), the Chinese High Technology Research and Development Programme (grant 2007AA061001), and the Programme of Innovative Engineering of the Chinese Academy of Sciences (grant CXTD-Z2005-4, KZCX2-YW-404) provided financial support for this work.

REFERENCES

Baker, A.J.M. and Brooks, R.R. 1989. Terrestrial higher plants which hyperaccumulate metallic elements. *Biorecovery* **1**, 89–92.

Baker, A.J.M., McGrath, S.P., Reeves, R.D., and Smith, J.A.C. 2000. Metal hyperaccumulator plants: A review of the ecology and physiology of a biochemical resource for phytoremediation of metal-polluted soil. In: *Phytoremediation of Contaminated Soil and Water*, pp. 85–107. (Terry, N. and Bañuelos, G., Eds.). Boca Raton, FL, Lewis.

Bert, V., MacNair, M.R., DeLaguerie, P., Saumitou-Laprade, P., and Petit, D. 2000. Zinc tolerance and accumulation in metallicolous and non-metallicolous populations of *Arabidopsis halleri* (Brassicaceae). *New Phytol.* **146**, 225–233

Brown, S.L., Chaney, R.L., Angle, J.S., and Baker, A.J.M. 1995a. Zinc and cadmium uptake by hyperaccumualtor *Thlaspi caerulescens* and metal tolerant *Silene vulgaris* grown on sludge amended soils. *Environ. Sci. Technol.* **29**, 1581–1585.

Brown, S.L., Chaney, R.L., Angle, J.S., and Baker, A.M.J. 1995b. Zinc and cadmium uptake by hyperaccumulator *Thlaspi caerulescens* grown in nutrient solution. *Soil Sci. Soc. Am. J.* **59**, 125–133.

Chen, T.B., Huang, Z.C., Huang, Y.Y., Xie, H., and Liao, X.U. 2003. Cellular distribution of arsenic and other elements in hyperaccumulator *Pteris nervosa* and their relations to arsenic accumulation. *Chin. Sci. Bull.* **48**, 1586–1591.

Ebbs, S.D. and Kochian, L.V. 1997. Toxicity of zinc to Brassica species: Implications for phytoremediation. *J. Environ. Qual.* **26**, 776–781.

Ebbs, S.D. and Kochian, L.V. 1998. Phytoextraction of zinc by oat (*Avena sativa*), barley (*Hordeum vulgare*), and Indian mustard (*Brassica juncea*). *Environ. Sci. Technol.* **32**, 802–806.

Francesconi, K., Visoottiviseth, P., Sridokchan, W., and Goessler, W. 2002. Arsenic species in an arsenic hyperaccumulating fern, *Pityrogramma calomelanos*: A potential phytoremediator of arsenic-contaminated soils. *Sci. Total Environ.* **284**, 27–35.

Guo, X.H. 1996. A new taxon of *Crassulaceae* from Anhui. *Acta Botanica Yunnanica* **18**(3), 297–229.

Küpper, H., Lombi, E., Zhao, F.J., and McGrath, S.P. 2000. Cellular compartmentation of cadmium and zinc in relation to other elements in the hyperaccumulator *Arabidopsis halleri*. *Planta* **212**, 75–84.

Liu, W., Shu, W.S., and Lan, C.Y. 2004. *Viola baoshanensis*, a plant that hyperaccumulates cadmium. *Chin. Sci. Bull.* **49**, 29–32.

Lombi, E., Zhao, F.J., Dunham, S.J., and McGrath, S.P. 2000. Cadmium accumulation in populations of *Thlaspi caerulescens* and *Thlaspi goesingense*. *New Phytol.* **145**, 11–20.

Lombi, E., Zhao, F.J., McGrath, S.P., Young, S.D., and Sacchi, G.A. 2001. Physiological evidence for a high-affinity cadmium transporter highly expressed in a *Thlaspi caerulescens* ecotype. *New Phytol.* **149**, 53–60.

Lu, R.K. 2000. *Analytical Methods for Soil and Agrochemistry*. Beijing, China, Agricultural Science and Technology.

McGrath, S.P. and Zhao, F.J. 2003. Phytoextraction of metals and metalloids from contaminated soils. *Curr. Opin. Biotechnol.* **14**, 277–282.

Raskin, I., Smith, R.D., and Salt, D.E. 1997. Phytoremediation of metals: Using plants to remove pollutants from the environment. *Curr. Opin. Biotechnol.* **8**, 221–226.

Reeves, R.D. and Baker, J.M. 2000. Metal-accumulating plants. In: *Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment*, pp. 193–230. (Raskin, H. and Ensley, B.D., Eds.). London, John Wiley.

Robinson, B.H., Leblanc, M., Petit, D., Brooks, R.R., Kirkman, J.H., and Gregg, P.E.H. 1998. The potential of *Thlaspi caerulescens* for phytoremediation of contaminated soils. *Plant Soil* **203**, 47–56.

Srivastava, M., Ma, L.Q., and Santos, J.A.G. 2006. Three new arsenic hyperaccumulating ferns. *Sci. Total Environ.* **364**, 24–31.

Tanhan, P., Kruatrachue, M., Pokethitiyook, P., and Chaiyarat, R. 2007. Uptake and accumulation of cadmium, lead and zinc by Siam weed [*Chromolaena odorata* (L.) King & Robinson]. *Chemosphere* **68**, 323–329.

Wei, C.Y., Chen, T.B., Huang, Z.C., and Zhang, X.Q. 2002. Cretan brake (*Pteris cretica* L.): An arsenic-accumulating plant. *Acta Ecologica Sinica* **22**, 777–778 (in Chinese).

Wei, S.H., Zhou, Q.X., Wang, X., Zhang, K.S., Guo, G.. L., Ma, L.N., and Qi, Y. 2005. A newly-discovered Cd-hyperaccumulator *Solanum nigrum* L. *Chin. Sci. Bull.* **50**, 33–38.

Wu, Z.Y. and Raven, P. H. 2001. *Flora of China*, vol. 8, pp. 221–251, Beijing, Science Press and St. Louis, Missouri Botanical Garden Press.

Xue, S.G., Chen, Y.X., Reeves, R.D., Baker, A.J.M., Lin, Q., and Fernando, D.R. 2004. Manganese uptake and accumulation by the hyperaccumulator plant *Phytolacca acinosa* Roxb. (Phytolaccaceae). *Environ. Pollut.* **131**, 393–399.

Yang, X.E., Li, T.Q., Long, X.X., Xiong, Y.H., He, Z.L., and Stoffella, P.J. 2006. Dynamics of zinc uptake and accumulation in the hyperaccumulating and non-hyperaccumulating ecotypes of *Sedum alfredii* Hance. *Plant Soil* **284**, 109–119.

Yang, X.E., Long, X.X., Ni, W.Z., and Fu, C.X. 2002. *Sedum alfredii* Hance: A new Zn hyperaccumulating plant first found in China. *Chin. Sci. Bull.* **47**, 1634–1637.

Yang, X.E., Long, X.X., Ye, H.B., He, Z.L., Calvert, D.V., and Stoffella, P.J. 2004. Cadmium tolerance and hyperaccumulation in a new Zn-hyperaccumulating plant species (*Sedum alfredii* Hance). *Plant Soil* **259**, 181–189.

Zhang, X.H., Liu, J., Huang, H.T, Chen, J., Zhu, Y.N., and Wang, D.Q. 2007. Chromium accumulation by the hyperaccumulator plant *Leersia hexandra* Swartz. *Chemosphere* **67**, 1138–1143.

Zhao, F.J., Lombi, E., Breedon, T., and McGrath, S.P. 2000. Zinc hyperaccumulation and cellular distribution in *Arabidopsis halleri*. *Plant Cell Environ*. **23**, 507–514.

Zhao, F.J., McGrath, S.P., and Crosland, A.R. 1994. Comparison of three wet digestion methods for the determination of plant sulfur by inductively coupled plasma atomic emission spectroscopy (ICP-AES). *Commun. Soil Sci. Plant Anal*. **25**, 407–418.