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Accumulation Properties of Cadmium in a Selected Vegetable-Rotation System of Southeastern China

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A rotation experiment was conducted in a greenhouse with three vegetable crops on red yellowish soil (RYS) and silt loamy soil (SLS) to study Cd accumulation in pak choi (*Brassica chinensis* L.), tomato (*Lycopersicon esculentum*), and radish (*Raphanus sativus* L.). Critical Cd concentrations in the two soils were evaluated for these vegetables based on human dietary toxicity. Cadmium was added as $Cd(NO_3)_2$ at a rate of 0−7.00 mg Cd kg^{-1} soil. Shoot growth was not inhibited by Cd except for radish grown on RYS. A small amount of Cd stimulated growth of the vegetables. Cadmium concentration in edible parts of the vegetables generally increased with Cd concentration in soils but was higher in RYS than SLS. The distribution of Cd in pak choi and tomato decreased in the order root > shoot > fruit, but the order was shoot > root for radish. When Cd content in the edible parts reached maximum contaminant levels for safety food standards, the soil total Cd concentrations were 0.327 and 0.120 mg kg^{-1} in RYS and 0.456 and 0.368 mg kg^{-1} in SLS for pak choi stem and radish, respectively, whereas ammonium acetate-extractable Cd was 0.066 and 0.089 mg kg^{-1} in RYS and 0.116 and 0.092 mg kg^{-1} in SLS for pak choi leaf and tomato, respectively, based on food safety standards.

KEYWORDS: Cadmium accumulation; food safety; red yellowish soil; silt loamy soil; vegetable crops

1. INTRODUCTION

There are increasing global concerns over environmental pollution because of its relation to human health. Heavy metals are pollutants of most concern because of their toxic and persistent nature (*1, 2*). Among all the toxic heavy metals, cadmium (Cd) is one of the most mobile elements. Anthropogenic activities such as industrial activities, fertilizer application, and sewage sludge disposal on land resulted in considerable accumulation of Cd in soil, and Cd is readily taken up by plants and transferred to aerial parts where it can be accumulated to a high level. Although plants do not require Cd for growth or reproduction, bioaccumulation of Cd in green plants and subsequent accumulation in the food chain exceeds all other trace elements because of its high mobility in soil (*1, 3–5*), particularly for those market garden products (*6*). Therefore, crops produced from Cd contaminated soils may be unsuitable or even detrimental for animal and human consumption (*7*). It was reported that 20% of agricultural soils in China (2.48×10^7 hm^2) were contaminated by heavy metals, in which more than 1.3×10^5 hm^2 was attributed to Cd (*8, 9*). The accumulation of potentially toxic Cd in topsoil could result in phytotoxicity at high concentrations and the transfer of Cd to the human diet from crop and vegetable uptake. It was reported that 1.46×10^8 kg of agricultural products were polluted by Cd every year in China, in which 5.0×10^7 kg of rice was polluted (*8, 10*), while there are few nationwide investigations on the vegetable Cd contamination status.

There is a raised concern over Cd pollution in food and potential risks to human health (*11–13*), as food is the main source of Cd to animals and most human beings (*14, 15*). The intake of edible plants by humans is the most direct path for soil Cd to affect human health. Cd is not only detrimental to human health through the food chain but also becomes phytotoxic at high concentrations. It is therefore imperative to control Cd concentrations in plants, especially in the edible parts of crops to ensure food safety. To limit the accumulation of soil Cd in crops, a good understanding of its accumulation properties in edible parts of different crops is required.

Previous studies of Cd accumulation in crops mainly focused on cereal crops such as rice, wheat, and maize (*16–18*), with little investigation of vegetable crops. Wang et al. used four extractants to evaluate the phytoavailability of metals in typical calcareous soils using pot experiments and emphasized the effect of soil properties but failed to develop critical soil Cd levels for potential dietary toxicity (*19*). The southeastern area of China is an important economic developmental region where a large quantity of fresh vegetables is consumed every day, and vegetable-rotation is a pervasive agricultural mode in this region. Cadmium distribution and accumulation differs greatly among

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vegetable varieties and tissues, as well as soil properties, which are influenced by vegetable-rotation, but the accumulation and distribution properties of Cd in different vegetables in a rotation system rarely were studied.

Maximum permissible concentrations (MPC) for Cd have been established by national and international health authorities (*20, 21*) (e.g., Australia and France), and the United Nations Food and Agriculture Organization and the World Health Organization (FAO/WHO) established a provisional tolerable daily intake (PTDI) of 70 μg Cd day^{-1} for humans. The need to protect consumers from Cd toxicity and ensure environmental safety is the scientific motive for setting guidelines on Cd concentrations in food and acceptable concentrations of Cd in agricultural soils. In the food consumption structure, the proportion of vegetables has increased with the improvement of living standards, and vegetables are also one of the most important pathways through which heavy metals enter the food chain and pose a potential threat to human health.

To ensure food and environmental safety, guidelines for acceptable concentrations of Cd in agricultural soils need to be established. Currently, a phytoavailability test of trace metals in soils is conducted by single extraction procedures, and a plant uptake test is used as the most immediate tool for potential risk assessment of heavy metals (*19, 22*). Because only a very small portion of soil total trace metals is actually available for crops, it is commonly accepted that the total trace metal concentration in soils is not a good indicator of phytoavailability nor a good tool for potential risk assessment (*19*). In addition, the concentration and distribution of Cd differed in plant species under the same conditions (*5*). Because of limited available data, the environmental pollution standards of heavy metals in agricultural soils established and used in China are still based on total content, with minimal consideration given to the difference in metal accumulation between the edible parts of crops and the poor relationship between total concentration and phytoavailability of heavy metals. Therefore, there are limitations in their applications. Studies indicate that water soluble, exchangeable, and loosely adsorbed metals are labile and thus available to plants (*23*) and that soil-extractable Cd may be a better indicator of bioavailability and toxicity than the total amount. Cadmium ions can be held to the soil surface, and the involved processes are dependent on many factors including soil composition, pH, redox status, and nature of the contaminant; thus, metal bioavailability and toxicity are different among soils (*24*).

The objectives of this study were to examine excess Cd effects on the growth of pak choi, tomato, and radish, to determine the accumulation and distribution of Cd in different tissues of commonly grown vegetable crops using greenhouse experiments, and to assess Cd phytoavailability in vegetables grown in typical soils of southeastern China.

2. MATERIALS AND METHODS

2.1. Soil Sample Collection and Preparation. Two typical soils in southeastern China (i.e., red yellowish soil (RYS) and silt loamy soil (SLS)) were collected at 0−20 cm depth from Deqing County and Hangzhou City, Zhejiang Province. Composite samples of the soils were hand-picked to remove large pieces of plant material, grit, earthworms, etc. and then were air-dried, ground, and passed through a 2 mm sieve prior to use. Relevant agrochemical properties of the soils are shown in **Table 1**. RYS contained larger amounts of organic C and total N, whereas SLS had higher cation exchange capacity (CEC) and concentrations of total P and NO_3^--N.

Table 1. Relevant Agrochemical Properties of Soils

soil properties	RYS	SLS
pH	5.12 ± 0.05	5.42 ± 0.08
organic C (g kg^{-1})	29.55 ± 0.29	11.50 ± 0.07
NO_3^--N (mg kg^{-1})	13.28 ± 0.36	173.46 ± 0.65
total P (mg kg^{-1})	345.33 ± 2.31	790.22 ± 2.56
total K (mg kg^{-1})	21.25 ± 0.55	20.45 ± 1.20
total N (g kg^{-1})	2.76 ± 0.01	0.83 ± 0.00
CEC (cmol kg^{-1})	12.47 ± 0.05	14.59 ± 0.03
total Cd (mg kg^{-1})	0.40 ± 0.02	0.52 ± 0.03
NH_4OAc Cd (mg kg^{-1})	0.12 ± 0.00	0.03 ± 0.00

The soil samples were treated with Cd as $Cd(NO_3)_2$ in an aqueous solution at loading rates of 0, 0.70, 1.00, 1.80, 2.50, 3.50, and 7.00 mg Cd kg^{-1} soil, and distilled water was added to adjust the soil moisture to 70% of its water-holding capacity. $NaNO_3$ was added to counterpoise NO_3^- in different treatments. All treatments were conducted in triplicate, and the pots with soil were randomly arranged in a greenhouse for 90 days. The vegetable crops used for this short-term rotation system included pak choi (*Brassica chinensis* L.), tomato (*Lycopersicon esculentum*), and radish (*Raphanus sativus* L.). Pak choi was sowed on April 12, 2005 and harvested on June 2, 2005; tomatoes were sowed on June 21, 2005 and harvested on December 5, 2005; and radishes were sowed on January 18, 2006 and harvested on April 17, 2006. Residual plant roots were removed after each crop harvest, and the soil with the same Cd treatment was mixed adequately before being apportioned evenly into three replications for the next crop.

2.2. Plant Sample Collection and Chemical Analysis. *2.2.1. Plant Sample Collection.* After harvest, plants were carefully removed from each pot and separated into root, shoot (including leaves and stems), and fruit. Roots and leaves were rinsed thoroughly with tap water first to remove all visible fine soil particles and then with ultrapure distilled water, blotted dry, and dried at 70 °C for 72 h. Dry weights (DW) of shoot, root, and fruit were recorded. Dry plant samples were ground using an agate mill and passed through a 60 mesh sieve prior to Cd analysis.

2.2.2. Total Cd in Soil and Plant. Soil samples were collected from pots after each vegetable harvest, thoroughly mixed, and air-dried. Subsamples of soil were ground to <0.149 mm using an agate mill for total Cd analysis. For determination of total Cd in soil, portions of each 0.20 g of soil were digested with a mix of 5 mL of HNO_3 + 1 mL of $HClO_4$ + 1 mL of HF. For plant samples, 0.200 g of root, shoot, or fruit was digested with a mix of 5 mL of HNO_3 + 1 mL of $HClO_4$. The resultant solutions were diluted to 25 mL using 2% HNO_3 and then filtered. The concentrations of Cd in the filtrate were determined using inductively coupled plasma-mass spectrometry (ICP-MS, Agilent, 7500a) following a standard procedure.

2.2.3. Available Cd in Soils. Ammonium acetate-extractable Cd was determined following the extraction procedure described by Van et al. (*25*). Briefly, fresh soil in portions equivalent to 6 g of oven-DW was shaken with 30 mL of 1 mol L^{-1} ammonium acetate solution (pH 7.0) for 2 h (200 rpm) at 25 °C, and then the suspension was centrifuged at 8000 rpm for 10 min and filtered through 0.45 μm filter paper. The determination of water-extractable Cd was performed as follows: 10–20 g of fresh soil was adjusted to its water holding capacity by adding deionized water. The suspensions were shaken for 2 h (200 rpm) at 25 °C and then centrifuged at 8000 rpm for 10 min and filtered through 0.45 μm filter paper. The Cd concentration in filtrate was analyzed by ICP-MS (Agilent, 7500a). All reagents used were of reagent grade.

2.3. Statistical Analyses. All soil and plant measurements were calculated on the basis of oven-DW (105 °C). All data were processed by Microsoft Excel (Microsoft, 2000), and the regression of linear statistical analyses and one-way analysis of variance (ANOVA) were performed using the statistical package SPSS (version 11.0). All figures were constructed using SigmaPlot 10.0.

3. RESULTS

3.1. Biomass Yield of Vegetables in Relation to External Cd Loading Rate. DWs of the three vegetable crops are summarized in **Figure 1**. Addition of Cd to soils up to 7.00 mg kg^{-1} had no visible toxic effect on shoot growth of all vegetable crops. The stimulating effect of Cd on the growth of both shoot

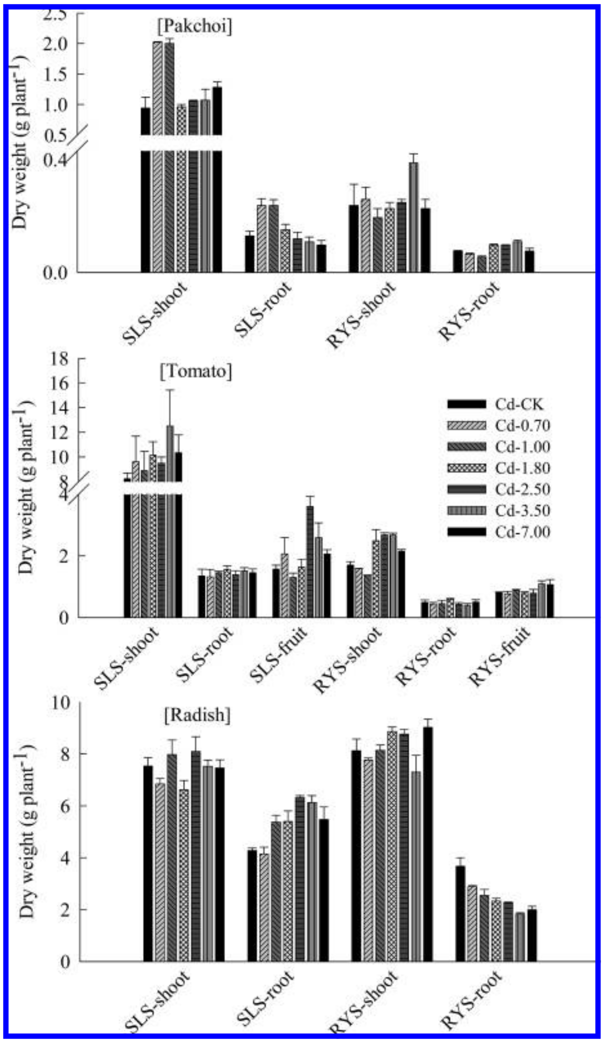

Figure 1. DW of three vegetable crops (pak choi, tomato, and radish) grown in SLS and RYS with different loading rates of Cd.

and root occurred at Cd rates of 1.00 and 3.50 mg kg^{-1} for pak choi and 3.50 and 1.80 mg kg^{-1} for tomato, respectively, in SLS and RYS. The stimulating effect of Cd on both shoot and root growth of radish occurred at 2.50 mg kg^{-1} in SLS, whereas in RYS, this stimulating effect on shoot growth of radish occurred at the high end (7.00 mg kg^{-1}), and no such effect was observed on radish root growth (**Figure 1**). Root DW of radish decreased gradually as the Cd rate increased and decreased to ~46% of the control at a soil Cd content of 6.31 mg kg^{-1} in RYS. Significant differences in the growth of vegetables were found between the two soil types, and the DW of vegetables was generally greater in SLS than RYS.

3.2. Extractable Cd in Soils after Plant Growth. Ammonium acetate- and water-extractable Cd increased with total soil Cd (**Figure 2**). Ammonium acetate extracted much more soil Cd than water in all cases. The extractability of Cd by ammonium acetate decreased with each crop harvested. For example, at the initial Cd loading rate of 7.00 mg kg^{-1} in RYS, ammonium acetate-extractable Cd was 46.6, 38.9, and 36.5% of total Cd, respectively, after planting pak choi, tomato, and radish, and those in SLS were 28.4, 23.2, and 21.4% respectively. The extractability of Cd in water varied significantly between the two soils and among the vegetable crops planted (**Figure 2**). Water-extractable Cd increased markedly with soil total Cd when it was <3.50 mg kg^{-1}, but the uplift trend was diminished subsequently, especially after radish growth. Water-extractable Cd concentrations were 0−0.056 and 0.004−0.028 mg kg^{-1}, respectively, in RYS and SLS after pak choi growth and became 0−0.040 and 0.0018−0.021 mg kg^{-1} after radish growth. After tomato harvest, water-extractable Cd was further decreased in the SLS (to 0.0005−0.0067 mg kg^{-1}) but was increased in the RYS (to 0.003−0.124 mg kg^{-1}). The reason for this differentiation in water-extractable Cd between the two soils after tomato is unclear. The relationship between ammonium acetate-extractable Cd and soil total Cd was better described by a linear equation ($r < 0.98$) than a quadratic equation ($r < 0.93$) (**Table 2**).

3.3. Accumulation and Distribution of Cd in Vegetable Crops. Cadmium concentration in vegetable tissues varied with Cd levels, vegetable species, and type of soils (**Figure 3**). In pak choi and tomato, Cd was mainly accumulated in root, with only a small portion of the absorbed Cd being transported to the aerial part, even less accumulated in fruit. Cadmium concentrations in both shoot and root of pak choi or tomato increased with increasing Cd loading rate, and more intensive increases appeared in root than shoot (**Figure 3**). Interestingly, the Cd concentration in radish was higher in shoots than roots with the same Cd loading rate, which is entirely different from pak choi or tomato.

ANOVA revealed that Cd accumulation in crop tissues was significantly affected by soil type. Cadmium concentrations in crops were significantly greater in RYS than SLS at the same Cd loading rate. For example, at total soil Cd of 1.84 mg kg^{-1}, Cd concentrations in the root, shoot, and fruit of tomato were 9.05, 5.68 and 0.63 mg kg^{-1}, respectively, in RYS, but the corresponding values were only 6.07, 4.29, and 0.29 mg kg^{-1} in SLS (**Figure 3**). Large differences in tissue Cd concentrations also were observed among the three vegetable species. Tomato contained higher Cd in roots and shoots than pak choi and radish, but Cd concentrations in tomato fruit were low.

Cadmium content in the edible parts of the vegetable crops was positively correlated with soil Cd content, which could be described by a linear or quadratic equation (**Table 3**). Cadmium concentrations in pak choi stem and radish root were best related to total soil Cd, with R^2 values of 0.985 and 0.990 for SLS and 0.955 and 0.990 for RYS, respectively, while the Cd concentration in pak choi leaf and tomato fruit were best related to ammonium acetate-extractable Cd, with R^2 values of 0.973 and 0.970 for SLS and 0.953 and 0.995 for RYS, respectively.

4. DISCUSSION

No inhibitory effects of Cd on shoot growth of three vegetables were observed even at the highest loading rate (7.00 mg kg^{-1}), and low to moderate levels of Cd (≤3.5 mg Cd kg^{-1} soil) had a stimulatory effect (**Figure 1**). For example, at a Cd level of 2.50 mg kg^{-1} soil, the DW of pak choi shoots was increased by 4.55 and 12.8%, respectively, in RYS and SLS, as compared to the control (**Figure 1**). Similar findings were reported in previous studies for a broad range of species (*26–29*). It seems that plants are able to defend and protect their integrity against mild environmental damaging stress. Various mechanisms have been suggested to explain the stimulatory effect, and one of the explanations is that metal ions may serve as activators of enzyme(s) in cytokinin metabolism, which accelerates the growth of plants (*26*). Second, low dose stress may cause changes in plant hormones and cytokinins that regulate plant growth and development. Hormones and cytokinins have been shown to cause an increase in chlorophyll accumulation; cytokinins also facilitate the synthesis and stabilization of LHCII (light-harvesting chlorophyll *a*/*b*−protein complex of photosystem II) and LHCI (light-harvesting chlorophyll *a*/*b*−protein complex of photosystem I), alter the relative distribu-

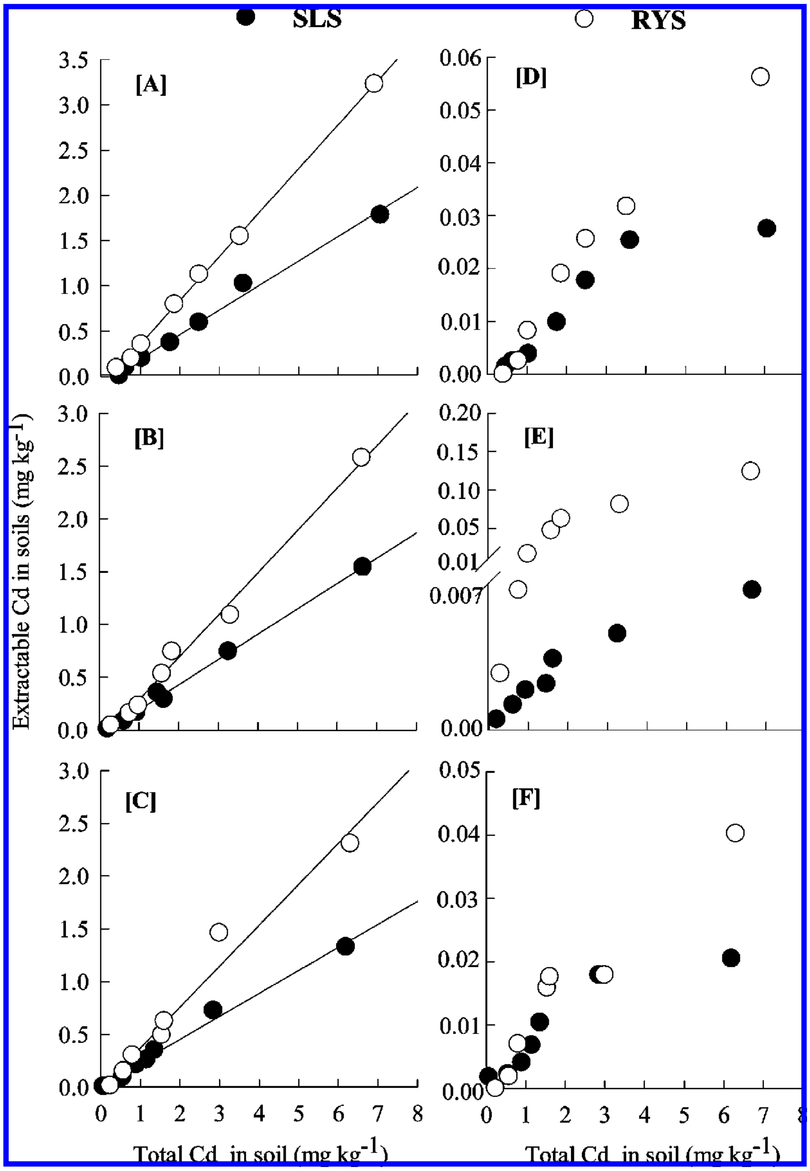

Figure 2. Changes of extractable Cd concentration in two soils after each vegetable crop planted. (**A**−**C**) NH_4OAc-extractable Cd concentration in soil after pak choi, tomato, and radish were planted, respectively. (**D**−**F**) Water-extractable Cd concentration in soil after pak choi, tomato, and radish were planted, respectively. Data are means of three replications; error bar represents the SD of duplicate results.

Table 2. Regression Analysis between Soil-Extractable Cd and Soil Total Cd after Each Vegetable Planted[a]

		SLS		RYS	
soil total Cd (x)	extractant (y)	regression equation	R^2	regression equation	R^2
pak choi	NH_4OAc	$y = 0.268x - 0.074$	0.998**	$y = 0.480x - 0.115$	0.999**
	water	$y = -0.001x^2 + 0.012x - 0.005$	0.983**	$y = -0.0007x^2 + 0.013x - 0.005$	0.991**
tomato	NH_4OAc	$y = 0.224x - 0.025$	0.997**	$y = 0.476x - 0.233$	0.989**
	water	$y = -0.0001x^2 + 0.0018x + 0.0003$	0.975**	$y = -0.003x^2 + 0.041x - 0.015$	0.971**
radish	NH_4OAc	$y = 0.273x - 0.060$	0.987**	$y = 0.444x - 0.092$	0.983**
	water	$y = -0.0008x^2 + 0.0087x - 0.0012$	0.959**	$y = -0.0005x^2 + 0.0092x - 0.0004$	0.937**

[a] y: Concentration of extractable Cd in soils and x: concentration of total Cd in soils.

tion of CPCs (chlorophyll−protein complex) of thylakoid membranes, and increase photosynthetic activity (*30*). Third, low molecular weight Cd-binding proteins might be synthesized in response to low stress of heavy metals by plants, and this type of protein has been shown to play a role in metal tolerance (*31*). In this study, vegetable crops, after being exposed to Cd, grew well without any visual phytotoxicity symptoms or yield reduction, even at moderate to high levels of Cd loading, which was consistent with previous findings showing little effects of Cd pollution on rice yield (*32, 33*). Accordingly, farmers may not receive sufficient early warning of Cd pollution or toxic concentration of Cd in grain based on yield change alone. Cadmium can be readily taken up by plants and thus affects food quality and, subsequently, human and animal health through contamination of the food chain.

As seen in **Figure 3A−D**, root tissue was the vegetative portion that had the highest concentration of Cd in pak choi and tomato. A similar Cd distribution also was reported by McKenna et al. (*34*) in lettuce and spinach. Generally, Cd concentrations in roots

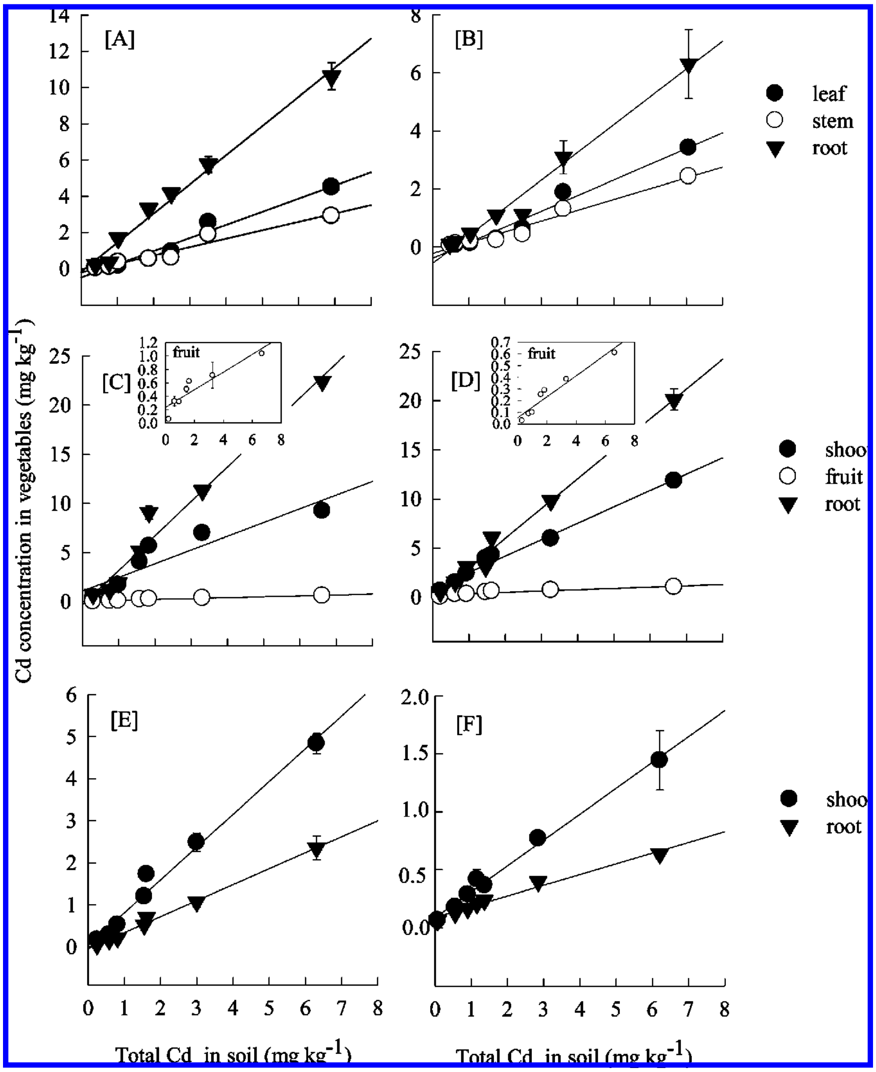

Figure 3. Accumulation and distribution of Cd in different tissues of three vegetable crops. (**A** and **B**) Cd accumulation in pak choi grown in RYS and SLS, respectively; (**C** and **D**) Cd accumulation in tomato grown in RYS and SLS, respectively; and (**E** and **F**) Cd accumulation in radish grown in RYS and SLS, respectively.

were higher than in shoots. Cadmium may be bound to peptides in the root, which acted as a barrier for the transport of Cd to shoot. Most of the root Cd in the plant was probably compartmented in the apoplast, including the surface adsorbed. Only a fraction of root Cd passed through xylem vessels and was transported to the shoot. Fruit Cd accumulation was the lowest as compared to other parts in the tomato, which was 1 order of magnitude lower than that in the whole shoot (**Figure 3A–D**). Lower fruit Cd accumulation in tomato possibly resulted from a combination of reduced root-to-shoot transfer of Cd at flowering stage and enhanced shoot-to-root retranslocation of Cd (*35*). The distribution of Cd in shoot and root of radish was an exception to this general rule. Cadmium concentrations in the shoot of radish were higher than those in root (**Figure 3E**,**F**). Similar results were observed in a previous study in assessing the availability of Cd to cherry-red radish (*5*). This unconventionality was attributed to the difference in Cd tolerance mechanisms between plant species and the accumulation of a high level of Cd in nonedible parts, which may limit the distribution of Cd in the edible portions of the plant. It is known that root to shoot translocation of Cd in the plant was partly due to transpiration and that the transpiration of radish might be strong; thus, more Cd was accumulated in the shoot, likely due to its high shoot biomass (**Figure 1**). Tudoreanu and Phillips (*36*) reviewed the mechanisms of Cd movement within plants and reasoned that existing models of Cd translocation appear to be genotype-specific and most likely related to genotypic differences in long distance transport processes. Therefore, the higher accumulation of Cd in radish shoot may result from the genotype of radish.

The accumulation properties of Cd in vegetables also were affected by plant species and soil type. Cadmium concentration in roots differed significantly among pak choi, tomato, and radish, and this variation could be attributed to variations in the expression or occurrence of high affinity Cd transporters in plasma membranes of root cells (*37*). Vegetable plants grown in RYS accumulated more Cd than those grown in SLS, mainly due to the difference in Cd availability between the two soils (**Figure 2**). Cadmium phytoavailability in RYS was greater than in SLS; more Cd was absorbed and translocated to shoot by xylem transport. In addition, the Cd concentration in vegetable plants grown in SLS may be partly diluted by their greater biomass than those in RYS.

It has long been recognized that soluble, exchangeable, and loosely adsorbed metals that are extractable to ammonium acetate are quite labile and readily available for plants (*23*). The extraction with water was to simulate the metal distribution equilibrium in soil pore water. The correlation between water-extractable Cd and total Cd was slightly poorer than that between ammonium-extractable Cd and total Cd. The ammonium acetate-extractable Cd in radish planted soil was less than that in pak choi planted soil at the same Cd loading rate. This was probably due to the decrease in total Cd in soils. This finding was consistent with the

Table 3. Regression Analysis between Cd in Edible Parts of Vegetables and Soil Cd Content (Total Cd and Extractable Cd)[a]

vegetable	soil types	soil Cd	regression equation	R^2
pak choi stem	SLS	total	$y = 0.400x - 0.133$	0.985**
		NH_4OAc-extractable	$y = 1.344x - 0.077$	0.970**
		water-extractable	$y = 4586x^2 - 57.81x + 0.201$	0.927**
	RYS	total	$y = 0.424x - 0.089$	0.955**
		NH_4OAc-extractable	$y = 0.940x - 0.047$	0.944**
		water-extractable	$y = 420.6x^2 + 29.17x + 0.013$	0.935**
pak choi leaf	SLS	total	$y = 0.147x - 0.018$	0.932**
		NH_4OAc-extractable	$y = 1.947x - 0.176$	0.973**
		water-extractable	$y = 6615x^2 - 81.88x + 0.212$	0.945**
	RYS	total	$y = 0.377x - 0.050$	0.951**
		NH_4OAc-extractable	$y = 0.787x - 0.002$	0.953**
		water-extractable	$y = 977.8x^2 + 27.07x - 0.005$	0.955**
tomato fruit	SLS	total	$y = 0.034x + 0.033$	0.883**
		NH_4OAc-extractable	$y = -0.110x^2 + 0.301x + 0.022$	0.970**
		water-extractable	$y = -1559x^2 + 44.13x$	0.941**
	RYS	total	$y = 0.146x - 0.006$	0.986**
		NH_4OAc-extractable	$y = -0.043x^2 + 0.339x + 0.020$	0.995**
		water-extractable	$y = 7.451x^2 + 3.23x + 0.044$	0.990**
radish root	SLS	total	$y = 0.116x + 0.007$	0.990**
		NH_4OAc-extractable	$y = 0.438x + 0.030$	0.992**
		water-extractable	$y = 24.73x - 0.003$	0.926**
	RYS	total	$y = 0.397x + 0.002$	0.990**
		NH_4OAc-extractable	$y = 1.024x - 0.003$	0.966**
		water-extractable	$y = 57.59x - 0.116$	0.940**

[a] *y*: Concentration of Cd in edible parts of vegetables and *x*: concentration of total or extractable Cd in soils.

conclusions of Eriksson et al., who found that the bioavailability of Cd, measured as cereal Cd uptake, was correlated to the total Cd concentration in soils (*38*). Cadmium bioavailability also varied substantially between RYS and SLS. The binding sites within SLS may have a higher affinity for Cd than RYS. Cadmium ions can be held to the soil by adsorption onto the surface of mineral particles, by complexation with humic substances, and by precipitation reactions (*39*). These complicated processes are dependent on many factors including soil composition, pH, and redox status. The availability of Cd was higher in RYS than SLS, partly because RYS had a lower pH and CEC (**Table 1**). In addition, vegetable plants grew better in SLS than RYS (**Figure 1**), and Cd was more depleted in SLS; therefore, the total Cd in the SLS rhizosphere was less than that in RYS.

There are significant correlations between extractable Cd in soil and Cd accumulation in the edible parts of vegetables (**Table 3**). Differences can be observed among pak choi, tomato, and radish as well as among total Cd, ammonium acetate-extractable Cd, and water-extractable Cd. The relationships between Cd concentrations of vegetables and water-extractable Cd could be described by a quadratic equation, suggesting that the accumulation of Cd in edible parts of pak choi and tomato become less efficient at higher water Cd concentrations. On the basis of correlation analysis (**Table 3**), it appeared that total soil Cd was a better soil test index for Cd phytoavailability in pak choi leaf and radish root, while ammonium acetate-extractable Cd was a better soil test index for Cd phytoavailability in pak choi stem and tomato fruit. To ensure environmental and food safety, an effort was made to develop guidelines for acceptable concentrations of potentially harmful Cd in agricultural soils. In this regard, two factors need to be considered: (1) the critical concentration of Cd above which a yield decrease or toxicity occurs and (2) the concentration of Cd above which food safety for humans or animals is negatively affected. Since the decrease in vegetable crop yield was not observed in this study (**Figure 1**), we mainly focused on the development of soil Cd standards based on food safety. According to the Chinese standard GB2762-2005, the maximum level of Cd for vegetable crops was 0.05 mg kg^{-1}. The critical Cd concentrations in edible parts of pak choi, tomato, and radish were calculated according to the regression equation in **Table 3**, and the results are shown in **Table 4**. By combining the results in **Table 3** with those in **Table 4**, tentative soil Cd thresholds for potential dietary toxicity can be obtained. From this study, it is proposed that total soil Cd is used as Cd thresholds for potential dietary toxicity in pak choi stem and radish and ammonium acetate-extractable Cd for potential dietary toxicity in pak choi leaf and tomato. Total Cd thresholds of potential dietary toxicity are 0.327 and 0.120 mg kg^{-1} in RYS and 0.456 and 0.368 mg kg^{-1} in SLS for producing pak choi stem and radish, respectively, whereas ammonium-extractable Cd thresholds of potential dietary toxicity are 0.066 and 0.089 mg kg^{-1} in RYS and 0.116 and 0.092 mg kg^{-1} in SLS for pak choi leaf and tomato consumption, respectively.

Table 4. Soil Cd Thresholds for Potential Dietary Toxicity in Edible Parts of Three Vegetable Crops Calculated from Regression Equations in **Table 3**

vegetables	index	RYS	SLS
pak choi stem	total Cd (mg kg^{-1})	0.327	0.456
	NH_4OAc-extractable Cd (mg kg^{-1})	0.103	0.094
	water-extractable Cd (mg kg^{-1})	0.0013	0.009
pak choi leaf	total Cd (mg kg^{-1})	0.265	0.459
	NH_4OAc-extractable Cd (mg kg^{-1})	0.066	0.116
	water-extractable Cd (mg kg^{-1})	0.0019	0.0025
tomato	total Cd (mg kg^{-1})	0.383	0.493
	NH_4OAc-extractable Cd (mg kg^{-1})	0.089	0.092
	water-extractable Cd (mg kg^{-1})	0.009	0.0012
radish	total Cd (mg kg^{-1})	0.120	0.368
	NH_4OAc-extractable Cd (mg kg^{-1})	0.051	0.045
	water-extractable Cd (mg kg^{-1})	0.0029	0.0022

In conclusion, the inhibitory effects of excess Cd on the growth of pak choi, tomato, and radish were not observed in terms of biomass yield, and low levels of Cd loading had a stimulatory effect on the growth of three vegetable crops. Ammonium acetate extracted more soil Cd than water after each vegetable planted, and the extractability of Cd by ammonium acetate decreased with each crop harvested. The accumulation and distribution of Cd in vegetable plants differed among soil types as well as vegetable species. Vegetable crops sequester Cd mainly in their roots, with a small portion being translocated to the aerial parts. The distribution of Cd in different parts of pak choi and tomato decreased in the order root > shoot > fruit, whereas that of Cd in radish was shoot > root. The cadmium concentration in edible parts of the vegetables in RYS was greater than that in SLS. For evaluating the Cd critical concentration of vegetables, both accumulation properties of Cd in edible parts of different crops and Cd availability in soils should be taken into consideration. Soil type, crop species, and Cd phytoavailability should be considered in the assessment of soil Cd thresholds for potential dietary toxicity.

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