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Influence of soil type and genotype on Cd bioavailability and uptake by rice and implications for food safety

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Abstract

Cadmium (Cd) entering the human body via the food chain is of increasing concern. This study investigates the effects of soil type and genotype on variations in the Cd concentrations of different organs of nine rice plants grown on two types of soils with two Cd levels. Cd concentrations in nine rice cultivars varied significantly with genotype and soil type ($P < 0.01$). The Cd concentration was higher in red paddy soil (RP) than in yellow clayey paddy soil (YP). The average Cd concentrations of different organs in three rice types were indica > hybrid > japonica for the Cd treatments and controls. The polished grain concentration in YP and RP soils had a range of 0.055–0.23 mg/kg and 0.13–0.36 mg/kg in the Cd treatment, respectively. Two rice cultivars in YP soil and five rice cultivars in RP soil exceeded the concentration limits in the Chinese Food Hygiene Standard (0.2 mg/kg). The Cd concentrations in roots, stems, and leaves were all significantly and positively correlated to that in polished grain in a single test. The Cd concentrations in polished grain were positively and significantly ($P < 0.01$) correlated with the calculated transfer factors of stem to grain and leaf to grain Cd transfer. The results indicated that the variations of Cd concentration in grain were related to Cd uptake and the remobilization of Cd from stem and leaf to grain. Also, the cultivars with a strong tendency for Cd-accumulation should be avoided in paddy soil with low soil pH and low organic matter content to reduce the risks to human health from high Cd levels in rice.

Key words: cadmium; red paddy soil; yellow clayey paddy soil; rice genotype; health risk

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Introduction

Cadmium (Cd) is one of the most toxic and mobile elements of all the toxic heavy metals (Zhao et al., 2009). It can be readily absorbed by rice and transferred to aerial organs where it can accumulate to high levels, possibly entering the food chain (Liu et al., 2005; Qian et al., 2010). Consequently, excessive intake of Cd in the diet may lead to impairment of kidney function and other chronic toxicities (Yeung and Hsu, 2005).

Paddy rice is the most important cereal in China. More than 60% of the human population relies on rice as a staple food and the amount represents 55% of all cereals consumed annually in China. However, more than 1.3×10^5 km^2 of agricultural soils are contaminated by Cd in China and 1.46×10^8 kg of agricultural products (including 5.0×10^7 kg of rice) are polluted by Cd (Wang, 2002). In many regions, paddy rice is heavily exposed to Cd, posing a health hazard to local residents. Rice products contaminated by Cd have also been reported in Liaoning, Guizhou, Jiangsu, Hunan, and Guangdong, as well as other provinces in China (Zheng et al., 2007; Zhu et al., 2008; Huang et al., 2008, 2009; Zhuang et al., 2009). Therefore, it is imperative to reduce toxic Cd accumulation in rice, especially in regions where paddy fields have been polluted.

Soil type and genotype have been found to be the main factors affecting the absorption of Cd in rice. Many studies showed that the uptake of Cd by plants was directly related to Cd bioavailability rather than to the total metal content (Kalis et al., 2007). This means the effect of soil type on Cd absorption in rice must be considered and environmental quality standards for soils urgently need to be updated to carefully control soil Cd contamination. Aside from Cd bioavailability in soil, the variation among rice cultivars needs to be considered when dealing with the protection of paddy fields. Large variations in grain Cd concentrations have been widely reported from rice fields and market-basket surveys (He et al., 2006; Qian et al., 2010). Considerable research has been undertaken to understand the factors controlling Cd bioavailability in soils (Kirkham et al., 2006). However, few studies have considered both the variation of Cd uptake by different rice cultivars and the bioavailability of Cd in different soil types.

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The present study was designed to investigate Cd accumulation in nine rice cultivars (of three types) grown on two main soil types in the middle and lower reaches of the Yangtze River. The overall aim of this study was: (1) to evaluate the effect of soil type and genotype on the variation of Cd absorption in rice, (2) to investigate the effect of physiological processes on genotypic variation in grain Cd absorption, and (3) to assess possible risks to human health among different cultivars on two soil types.

1 Materials and methods

1.1 Soil

Two typical paddy soils, red paddy soil (RP) and yellow clayey paddy soil (YP), were sampled from the surface layer (0–15 cm depth) of uncontaminated paddy fields for pot experiments. Red paddy soil (typical Fe-accumuli-stagnic anthrosols) derived from Quaternary red clay was collected from Yingtan City, Jiangxi Province, China (28°12′N, 116°57′E). Yellow clayey paddy soil (Typical Fe-accumuli-stagnic Anthrosols) derived from alluvial deposits, was collected from Changshu City, Jiangsu Province, China (31°36′N, 120°35′E). Table 1 lists the basic soil physico-chemical properties.

Soil (7 kg) was placed in 35 cm diameter, 30 cm tall pots. Two Cd levels were studied: 0.6 mg/kg of Cd added and a control with no Cd added. $CdSO_4 \cdot 8/3H_2O$ was dissolved in deionized water and poured slowly into the soil as the soil was mixed. The thoroughly mixed soil was stored in pots and incubated at 80% water holding capacity for 3 months.

1.2 Rice cultivars

Nine rice cultivars of three types were used in this experiment. These were hybrid rice (cvs. Denong 2000 (DN), Tianxie 6 (TX) and Gangyou 118 (GY)), japonica rice (cvs. Wanjing 9707 (WJ), Ningjing 1 (NJ1) and Nanjing 32 (NJ32)), and indica rice (cvs. Zhongyu 1 (ZY), Tesanai 2 (TS) and Zhe 1500 (ZHE)). These cultivars are commonly planted in the middle and lower reaches of the Yangtze River and in the southern coastal regions of China. Rice seeds were submerged in a water bath for about 48 hr at room temperature (20–25°C and germinated under moist conditions (seeds were covered with two layers of moist gauze) at 32°C for another 30 hr. The germinated seeds were grown in an uncontaminated paddy field. After 15 days, the seedlings were transplanted into the pots. The pot soil was maintained under flooded conditions with 2–3 cm of water above the soil surface during the entire growth period.

1.3 Experimental design

The pot trial was carried out at Zhongshan Botanical Garden in Nanjing City during the rice-growing season (mid-May to early October) in a greenhouse. The pots were arranged in a randomized complete block design with three replicates. Nitrogen, phosphorus and potassium fertilizers were applied to each pot with 1 g urea (460 g N /kg), 0.28 g $Ca(HPO_4)_2$ and 0.7 g K_2SO_4, respectively.

1.4 Analytical methods

Soil pH was measured using a glass electrode at a soil:water ratio of 1:2.5 (g/mL); organic carbon content was determined by wet digestion following the method of Nelson and Sommers (2001) and cation exchange capacity (CEC) was measured by NH_4OAc leaching as described by Lu (2000). Soil texture was analyzed using the method of Bowman and Hutka (2002). Total soil Cd was determined by graphite furnace atomic absorption spectrometry (SpetrAA 220Z, Australia) with mixed acid digestion (HNO_3-$HClO_4$-HF) (Amacher, 2001). A certified sediment reference material (GBW07456 from the National Research Center for Standard Materials in China) with a Cd concentration of (0.56±0.04) mg/kg was used with soil digestions. The available-Cd content was determined by the EDTA-Na_2 extraction method (Li et al., 2003). The Fe oxide content was extracted with acidified ammonium oxalate (Scheinost and Schwertmann, 1999).

At maturity, whole rice plants were harvested and first washed thoroughly with tap water and then with deionized water. The plants were divided into roots, leaves, stems and grain and then oven-dried at 70°C to a constant weight. The oven-dried samples were ground with a stainless steel grinder (FW-80, China). The grains were air-dried to a constant weight, and polished with a rice polishing machine (LTJM-12, China). The samples of polished rice were oven-dried at 60°C to a constant weight, then ground with a stainless steel grinder (FW-80, China). The Cd concentrations of the samples were determined by graphite furnace atomic absorption spectrometry (SpetrAA 220Z, Australia) following HNO_3-H_2O_2 digestion procedures. A certified rice reference material (GBW 10010 from the National Research Center for Standard Materials in China) with a Cd concentration of (0.087±0.005) mg/kg was used with all rice sample digestion.

1.5 Data analysis

1.5.1 Statistical analyses

Data were analyzed using the statistical package SPSS 16.0 and Excel 2003 for Windows, using significance levels of $P < 0.05$ and $P < 0.01$. Two-way variance analysis (ANOVA) was carried out and followed by the Tukey

Table 1 Basic physico-chemical properties of the soils

Soil	pH	OC (g/kg)	CEC (mg/kg)	Fe oxide (mg/kg)	Clay (%)	Cd concentration (mg/kg)	
						Total	EDTA-Na_2
RP	5.07	12.03	9.39	1.99	18.8	0.25	0.18
YP	6.15	26.72	17.98	4.11	26.1	0.33	0.16

OC: soil organic carbon, CEC: cation exchange capacity.

HSD (honestly significant difference) test. Also, Pearson correlation coefficients were calculated to determine the relationships between different variables.

1.5.2 Transfer factors (TF)

Stem to grain transfer factors (TF_{stem}) and leaf to grain transfer factors (TF_{leaf}) were calculated as the following Eqs. (1) and (2):

$$TF_{stem} = \frac{C_{grain}}{C_{stem}} \quad (1)$$

$$TF_{leaf} = \frac{C_{grain}}{C_{leaf}} \quad (2)$$

where, C_{grain} (mg/kg), C_{stem} (mg/kg) and C_{leaf} (mg/kg) are the Cd concentrations of the polished grain, respectively.

1.5.3 Heath risk assessment

The health risk from Cd contamination through the consumption of rice grown on two soil types with two Cd levels was assessed based on the target hazard quotient (THQ) (US EPA, 2000). A THQ of less than 1 means the exposed population is assumed to be safe. The THQ value of Cd was determined by Eq. (3):

$$THQ = \frac{E_F E_D F_{IR} C}{R_{FD} W_{AB} T_A} \times 10^{-3} \quad (3)$$

where, E_F (365 days/yr) is exposure frequency; E_D (70 years) is the exposure duration; F_{IR} (g/(person·day)) is the food (rice) ingestion rate, assuming the average daily rice ingestion rates for adults of 376 g/(person·day) (Zou et al., 2008); C (mg/kg) is the Cd metal concentration in the food; R_{FD} (mg/(kg·day)) is the oral reference dose; W_{AB} (kg) is the average body weight, as used in a previous study by Wang et al. (2005), of 56 kg for adults; and T_A is the averaged exposure time for noncarcinogens (365 days/yr, number of exposure years assumed as 70). Oral reference doses for Cd were based on 1×10^{-3} mg/(kg·day) (US EPA, 2000).

2 Results

2.1 Genotypic differences vs. Cd concentrations in different organs

There were wide variations among the nine rice cultivars in the Cd concentrations of different rice plant organs for the two soil types (Table 2). In general, Cd concentrations in rice increased with the level of Cd contamination. The average Cd concentrations decreased in the sequence: root > stem > leaf > polished grain for both Cd treatments and controls. The mean values for roots, stems, leaves and polished grain were 0.86, 0.23, 0.086 and 0.046 mg/kg for the control, respectively; and the corresponding values were 3.83, 1.3, 0.40 and 0.19 mg/kg for the Cd treatment.

Significant differences in Cd concentrations were found in the four parts (roots, stems, leaves, and polished grain) of the nine rice varieties, depending upon soil type and genotype ($P < 0.01$) (Table 3). The Cd concentrations among the nine rice cultivars in different organs in RP were higher than in YP at the two levels of Cd contamination. In general, indica rice (cv. ZHE) had significantly higher Cd concentrations in different organs, and japonica rice (cv. NJ32) had lower concentrations (Table 2).

The variation in Cd content in polished grain among nine cultivars was significant ($P < 0.01$). For Cd treatments, the grain concentration of Cd in YP had a range of 0.055–0.23 mg/kg, and in RP of 0.13–0.36 mg/kg (Table 2). Cd levels in polished grain of two rice cultivars in YP and five rice cultivars grown on the Cd-treated RP exceeded the National Food Hygiene Standard of China (i.e., 0.2 mg/kg); while polished grain in the control treatment did not exceed this standard .

The variation in Cd concentration among the three rice types in different organs was significant ($P < 0.05$). In general, the japonica rice had the lowest Cd concentrations. The average Cd concentrations of different organs in three

Table 2 Cd concentrations (mg/kg) of different organs among nine rice cultivars

Soil type	Genotype	Cultivar	Root		Stem		Leaf		Polished grain	
			CK	Cd	CK	Cd	CK	Cd	CK	Cd
RP	Hybrid	DN	1.22 b	5.18 bc	0.45 c	1.86 c	0.14 c	0.77 a	0.071 b	0.21 b
		TX	1.23 b	4.47 cd	0.37 d	1.73 cd	0.13 c	0.53 cd	0.076 b	0.17 c
		GY	1.21 b	4.47 cd	0.30 e	1.62 d	0.14 c	0.63 b	0.051 c	0.20 b
	Japonica	WJ	0.77 c	5.34 b	0.24 f	1.23 e	0.098 d	0.42 ef	0.052 c	0.13 d
		NJ1	0.83 c	4.00 d	0.24 f	1.76 cd	0.047 f	0.50 de	0.016 d	0.17 c
		NJ32	0.85 c	5.18 bc	0.25 f	1.73 cd	0.073 e	0.41 f	0.017 d	0.16 c
	Indica	ZY	1.41 a	4.88 bc	0.58 a	2.06 b	0.16 b	0.59 bc	0.068 b	0.20 b
		TS	1.51 a	6.21 a	0.52 b	2.26 a	0.18 a	0.79 a	0.092 a	0.33 a
		ZHE	1.46 a	6.86 a	0.48 bc	2.27 a	0.17 a	0.79 a	0.094 a	0.36 a
		Average	1.17	5.18	0.38	1.83	0.13	0.60	0.060	0.22
YP	Hybrid	DN	0.59 b	2.69 bc	0.12 b	0.91 ab	0.053 b	0.23 a	0.039 b	0.17 b
		TX	0.54 b	2.64 c	0.13 a	0.89 bc	0.064 a	0.24 a	0.037 b	0.15 b
		GY	0.38 c	2.51 c	0.067 d	0.75 d	0.051 b	0.23 a	0.029 c	0.11 c
	Japonica	WJ	0.38 c	1.81 d	0.051 e	0.53 ef	0.033 d	0.14 d	0.017 d	0.12 c
		NJ1	0.39 c	1.74 d	0.047 ef	0.59 e	0.033 d	0.15 d	0.0089 d	0.090 d
		NJ32	0.36 c	1.63 d	0.041 f	0.50 f	0.029 d	0.15 d	0.010 d	0.055 e
	Indica	ZY	0.74 a	2.97 abc	0.072 d	0.83 c	0.030 d	0.18 c	0.043 b	0.16 b
		TS	0.75 a	3.21 a	0.11 bc	0.93 ab	0.044 c	0.21 b	0.052 a	0.22 a
		ZHE	0.72 a	3.11 ab	0.10 c	0.96 a	0.040 c	0.24 a	0.052 a	0.23 a
		Average	0.54	2.48	0.08	0.77	0.042	0.20	0.032	0.15

CK: no added Cd, Cd: added Cd.
Different letters in a column indicate significant differences between the cultivars ($P = 0.05$).

Table 3 Analysis of variance of effects of soil type and genotype on Cd concentrations in different organs among nine rice cultivars

Treatment	organ	Soil type	Genotype	Soil type × genotype
CK	Root	< 0.01	< 0.01	< 0.01
	Stem	< 0.01	< 0.01	< 0.01
	Leaf	< 0.01	< 0.01	< 0.01
	Polished grain	< 0.01	< 0.01	< 0.01
Cd	Root	< 0.01	< 0.01	< 0.01
	Stem	< 0.01	< 0.01	< 0.01
	Leaf	< 0.01	< 0.01	< 0.01
	Polished grain	< 0.01	< 0.01	< 0.01

rice types varied in the sequence of indica > hybrid > japonica for both Cd treatments and controls (Table 4).

2.2 Relationships between Cd concentrations in different organs and translocation characteristics among nine rice cultivars

There were significant positive correlations in Cd concentrations between root, stem, leaf and polished grain for both controls and Cd treatments (Table 5). The results indicated the variation of Cd concentrations in rice may result from differences in Cd uptake.

There were significant differences among TF_{stem} and TF_{leaf} in different cultivars ($P < 0.05$) (Table 6). In general, the indica rice (cv. ZHE) had significantly higher TF_{stem} and TF_{leaf}, and the japonica rice (cv. NJ32) had lower TF (Table 6). This is consistent with the Cd concentrations in polished grain. The TF values of the nine rice cultivars varied in the sequence of $TF_{leaf} > TF_{stem}$ in two Cd level tests. There was a significant correlation between Cd concentration in polished grain and TF_{stem} and TF_{leaf} ($P < 0.01$) (Table 7). The results suggested that the variation of Cd concentrations in grain may result from differences in Cd transfer from stems and leaves.

2.3 Health risk analysis on the basis of dietary intake of Cd and target hazard quotients

The THQ values for the nine rice varieties varied as follows: 0.11–0.64 and 0.89–2.41 for the control and Cd treatments in RP, and 0.060–0.36 and 0.37–1.55 for the control and Cd treatments in YP, respectively (Fig. 1). The THQs values were higher for all rice varieties grown in RP when compared to YP at the two Cd levels. The THQs for Cd via rice consumption were less than 1 for all varieties grown in the control treatment (Fig. 1a). For the Cd treatment, all rice varieties except WJ in RP and the DN, TX, ZY, and ZHE varieties in YP had THQs via rice consumption greater than 1, indicating a risk existed of noncarcinogenic effects (Fig. 1b). The results indicated rice grown in RP contaminated by Cd had a higher risk to human health than rice grown in YP, and Cd-contaminated indica and hybrid had comparatively higher health risks than japonica.

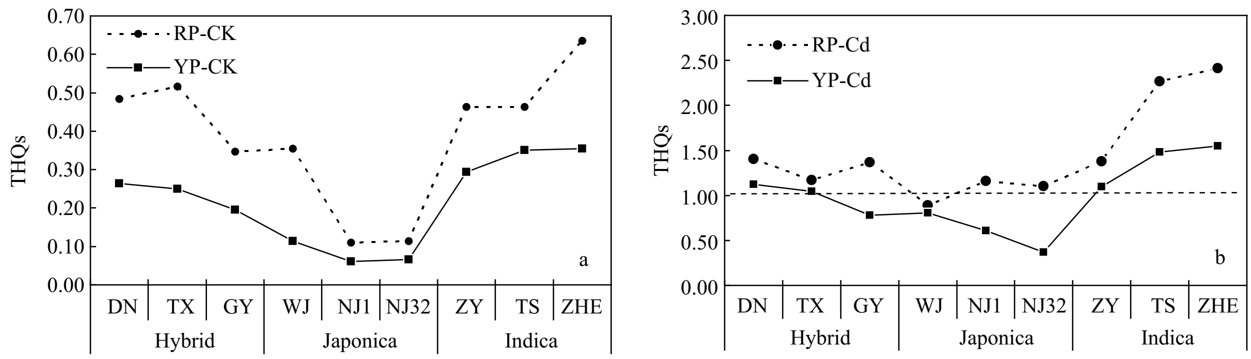

Fig. 1 THQ values via consumption of the nine rice varieties grown on two soil types at two Cd levels.

Table 4 Average Cd concentration (mg/kg) in different organs of three rice types

Soil type	Genotype	CK				Cd			
		Root	Stem	Leaf	Polished grain	Root	Stem	Leaf	Polished grain
RP	Hybrid	1.22 b	0.37 b	0.18 a	0.066 a	4.71 b	1.73 b	0.64 a	0.19 b
	Japonica	0.81 c	0.24 c	0.073 b	0.028 b	4.84 b	1.57 b	0.44 b	0.16 b
	Indica	1.46 a	0.53 a	0.17 a	0.085 a	5.98 a	2.20 a	0.73 a	0.30 a
YP	Hybrid	0.50 b	0.10 a	0.056 a	0.035 b	2.61 b	0.85 a	0.24 a	0.15 ab
	Japonica	0.38 b	0.046 b	0.032 b	0.012 c	1.73 c	0.54 b	0.15 b	0.088 b
	Indica	0.74 a	0.093 a	0.038 b	0.049 a	3.10 a	0.91 a	0.21 a	0.20 a

Different letters in a column indicate significant differences between the cultivars ($P = 0.05$).

Table 5 Correlation coefficients in Cd concentrations between grain and leaf, stem and root of rice in two Cd levels

Treatment	RP			YP		
	Leaf	Stem	Root	Leaf	Stem	Root
Polished grain (CK)	0.91**	0.77**	0.83**	0.41*	0.77**	0.89**
Polished grain (Cd)	0.81**	0.85**	0.71**	0.82**	0.86**	0.84**

* Significant ($P = 0.05$), ** significant ($P = 0.01$).

Table 6 TF of Cd from stem and leaf to grain among nine rice cultivars in two soils

Soil type	Genotype	Cultivar	CK		Cd	
			TF_{stem}	TF_{leaf}	TF_{stem}	TF_{leaf}
RP	Hybrid	DN	0.16 d	0.51 ab	0.11 c	0.27 d
		TX	0.21 ab	0.59 a	0.10 cde	0.32 cd
		GY	0.17 cd	0.38 c	0.13 b	0.32 cd
	Japonica	WJ	0.22 a	0.53 ab	0.11 c	0.31 cd
		NJ1	0.067 f	0.35 c	0.10 cde	0.34 bc
		NJ32	0.068 f	0.23 d	0.094 e	0.40 ab
	Indica	ZY	0.12 e	0.44 bc	0.10 cde	0.34 bc
		TS	0.18 bcd	0.51 ab	0.15 a	0.42 a
		ZHE	0.19 abc	0.55 ab	0.16 a	0.45 a
		Average	0.15	0.45	0.12	0.36
YP	Hybrid	DN	0.34 c	0.73 c	0.18 cd	0.72 cd
		TX	0.29 cd	0.58 d	0.17 cd	0.63 de
		GY	0.43 b	0.57 d	0.15 d	0.50 ef
	Japonica	WJ	0.33 c	0.51 d	0.22 ab	0.83 bc
		NJ1	0.19 d	0.28 e	0.15 d	0.59 de
		NJ32	0.24 cd	0.34 e	0.11 e	0.37 f
	Indica	ZY	0.61 a	1.43 a	0.19 bc	0.88 b
		TS	0.48 b	1.19 b	0.24 a	1.07 a
		ZHE	0.53 ab	1.32 ab	0.24 a	0.95 ab
		Average	0.38	0.77	0.19	0.73

Different letters in a column indicate significant differences between the cultivars (P = 0.05).

3 Discussion

3.1 Effect of soil type on Cd bioavailability

Soil type significantly affected the Cd absorption in rice. Huang et al. (2008) studied Cd accumulation in three soil types with different physical and chemical properties in an experiment with potted plants, and found the Cd concentration in rice on different type soils was: > paddy soil > Wushan soil, which was the reverse of the soil pH order. In Wushan soil, the addition of Cd did not significantly increase the rice Cd concentration. A pot experiment was also conducted to document the effects of soil type and genotype on the bioavailability of Cd. Two rice cultivars were grown on two soils. One was red soil with pH 4.95, and another was paddy soil with pH 6.54. The Cd concentration was greater in soil with a low pH and low organic carbon, and ranged from 0.250 to 0.623 mg/kg in the grain (Li et al., 2005). In the present study, YP had a higher pH and organic carbon level, and the Cd concentrations among the nine rice cultivars in RP were higher than in YP at the two Cd levels.

Soil pH was found to play the most important role in determining the adsorption of Cd at soil binding sites and in Cd speciation, solubility, and mobility in the soil solution (Zhao et al., 2010). The mobility and bioavailability of Cd increased with lower soil pH (Wang et al., 2006). This enhanced the uptake of Cd by rice and thereby posed a threat to human health (Zhao et al., 2009). Apart from soil pH, organic matter content in soil is also one of the most important soil properties affecting Cd availability (He and Singh, 1993). Organic matter is a major contributor in the ability of soils to retain Cd in an exchangeable form (Sauvé et al., 2003). Hettiarachchi et al. (2003) reported that Cd adsorption onto soil constituents declined with decreased soil organic matter content. In the present study, soil pH and organic matter may be the main factors responsible for the higher Cd availability in RP.

Table 7 Correlation coefficients between Cd concentration in grain and TF_{stem} and TF_{leaf} in nine rice varieties

Item	Cd concentration in polished grain			
	RP-CK	RP-Cd	YP-CK	YP-Cd
TF_{leaf}	0.83**	0.67**	0.87**	0.86**
TF_{stem}	0.75**	0.90**	0.79**	0.88**

** Significant (P= 0.01), RP-CK: control treatment in RP; RP-Cd: Cd treatment in RP; YP-CK: control treatment in YP; YP-Cd: Cd treatment in YP.

3.2 Effect of genotype on Cd absorption

In the present study, the concentration differences between the highest and lowest values were 3–6 times in polished grain, and 1.5–2 times in other organs. The uptake and translocation of Cd to the consumed parts of rice varies greatly with cultivars. In a slightly Cd-contaminated soil (1.09 mg/kg), the difference in grain Cd concentrations among 138 rice cultivars was 9.1 times (Zeng et al., 2008). Some researchers have shown significant differences in the accumulations of Cd in roots, straw and grain of different cultivars (He et al., 2006; Liu et al., 2007a). The variation of Cd uptake and accumulation in different rice cultivars were related to their root oxidation abilities (Liu et al., 2006), root acidifications and root organic acid secretions (Liu et al., 2007b).

Considerable numbers of studies have documented not only a significant variation in Cd concentration between different rice cultivars, but also in different rice types. However, there were many inconsistencies. Wang and Gong (1996) suggested hybrid rice had more Cd absorption than conventional rice during a hydroponic experiment. Li et al. (2003) have reported the same results in a field experiment. However, Zhong et al. (2006) showed polished grain Cd accumulation in rice types was indica > hybrid > japonica through a field experiment, confirming our results. Römken et al. (2011) demonstrated in a field experiment that indica had higher Cd absorption in low Cd soils and only unpolluted soils were suitable for indica cultivars. The results related to Cd concentrations in different rice types show many differences and contradictions caused by different experimental conditions such as differences in environment and in the cultivars selected; thus it was difficult to obtain consistent results. However, even if some differences existed in the test conditions, there were consistent results in variety screenings based on many reports. For example, the varieties Wuyunjing 3 and Wuyunjing 7 accumulate low levels of Cd while Shanyou 63 and Liangyoupeijiu accumulate higher levels (Arao and Ae, 2003; Li et al., 2003; Liu et al., 2003; Ishikawa et al., 2005). Therefore, cultivars which accumulate high levels of Cd should be avoided in agricultural production as far as possible.

In this study, there were significant positive correlations in Cd concentration between roots, stems, leaves and polished grain for both treatments (Table 5). Results indicated that the variation of Cd concentrations in rice may result from differences in Cd uptake. He et al. (2006) reported a significant linear correlation between the Cd concentration in straw and in brown rice (r = 0.955, n = 38, P < 0.01). Yan et al. (2010) showed there were significant correlations between grain Cd concentrations and shoot or root Cd concentrations in thirty-five rice cultivars (P < 0.01).

There were significant differences in TF_{stem} and TF_{leaf} among the different cultivars (P < 0.01), and significant positive correlations exist between the Cd concentrations in polished grain and in the TF_{stem} and TF_{leaf} (P < 0.01). The results suggest that the variation of Cd concentrations in grain may be related to the differences of Cd transfer from stem and leaf. Harris and Taylor (2001) suggested the elevated remobilization of Cd from leaves and stems to the maturing grain may result in the high accumulation of Cd in durum wheat grain. Kashiwagi et al. (2009) also reported the rapid decrease in the Cd content in rice leaves and suggested that leaves were the most important source of Cd accumulation in grain. They suggested a high level of Cd accumulation in grain probably reflects the redistribution of Cd. Therefore, when breeding cultivars for low grain Cd accumulation rates, researchers need to select cultivars which weakly transfer cadmium from stems and leaves to grain.

3.3 Target hazard quotients (THQ) for Cd and implications for food safety

THQs are widely used during the evaluation of health risks caused by the consumption of metal-contaminated food crops (Chary et al., 2008). In the present study, during the Cd treatment, all rice varieties except WJ in RP and the DN, TX, ZY, and ZHE varieties in YP had THQs of greater than 1 based on rice consumption (Fig. 1), which could lead to a health risk. Of the three types of rice studied, indica and hybrid pose a greater risk to human health than japonica. The values of the THQs were higher in RP than in YP at the two Cd levels. This shows there will be a greater potential health risk in southern China where soil pH tends to be lower. Also, without considering other edibles, the THQs of the two cultivars, cvs. ZHE and TX, exceeded 0.5 and in three cultivars, cvs. DN, ZY and TS, were about 0.5 in RP for the control treatment. This will still pose a potential risk to local residents. Therefore, great care must be taken in cultivar selection when growing rice in regions where inherent soil characteristics lead to the presence of high soil Cd levels in a readily available form. Growing high Cd cultivars in areas with low organic matter and on acid soils should be avoided.

4 Conclusions

Soil type and genotype significantly affected Cd absorption in rice (P < 0.01). There were significant genotypic differences in Cd concentrations in all rice plant organs. The indica variety had higher Cd absorption rates than the other two types. The variation in Cd concentration in different cultivars was dependent on absorption and remobilization from leaf and stem to grain among the nine cultivars.

Because of differences in soil properties, three rice cultivars in RP exceeded the maximum allowable Cd concentration set by the Chinese Food Hygiene Standard (0.2 mg/kg), although levels were below this standard in YP. Soil pH and organic matter content might be the main factors affecting the Cd availability in the two soils. Therefore, establishing a safe Cd threshold for paddy soil based on specific soil properties is necessary; screening of rice varieties with lower Cd translocation from soil to rice grains could ensure the safety of agricultural products.

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