

Water management affects arsenic and cadmium accumulation in different rice cultivars

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Abstract Paddy rice (*Oryza sativa* L.) is a staple food and one of the major sources of dietary arsenic (As) and cadmium (Cd) in Asia. A field experiment was conducted to investigate the effects of four water management regimes (aerobic, intermittent irrigation, conventional irrigation and flooding) on As and Cd accumulation in seven major rice cultivars grown in Zhejiang province, east China. With increasing irrigation from aerobic to flooded conditions, the soil HCl-extractable As concentrations increased significantly and the HCl-extractable Cd concentrations decreased significantly. These trends were consistent with the As and Cd concentrations in the straw, husk and brown rice. Water management both before and after the full tillering stage affected As and Cd

accumulation in the grains. The intermittent and conventional treatments produced higher grain yields than the aerobic and flooded treatments. Cd concentrations in brown rice varied 13.1–40.8 times and As varied 1.75–8.80 times among the four water management regimes. Cd and As accumulation in brown rice varied among the rice cultivars, with Guodao 6 (GD6) was a low Cd but high-As-accumulating cultivar while Indonesia (IR) and Yongyou 9 (YY9) were low As but high-Cd-accumulating cultivars. Brown rice Cd and As concentrations in the 7 cultivars were significantly negatively correlated. The results indicate that As and Cd accumulated in rice grains with opposite trends that were influenced by both water management and rice cultivar. Production of ‘safe’ rice with respect to As and Cd might be possible by balancing water management and rice cultivar according to the severity of soil pollution.

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Introduction

Arsenic (As) and cadmium (Cd) are two of the most toxic trace elements to plants and humans. Soil contamination by As and Cd occurs in many countries as a result of anthropogenic activities, particularly wastewater and solid waste disposal and intensive use of agrochemicals. Although As and Cd lack any essential function in plants, they can be taken up and accumulated in plants and subsequently enter the food chain to pose a risk to human health (Abedin et al. 2002; Verbruggen et al. 2009). Rice (*Oryza sativa* L.) is an important cereal crop second only to wheat worldwide. However, rice accumulates much higher concentrations of As and Cd in the shoots and grains compared with other cereals (wheat, barley and maize) (Williams et al. 2007), which makes rice contamination by As and Cd a global environmental health concern (Meharg and Rahman 2003; Tsukahara et al. 2003; Mondal and Polya 2008; Williams et al. 2009). There is an urgent need to develop strategies for reducing As and Cd uptake and to limit their translocation from roots to shoots or loading into the grains to minimize the health impacts of As and Cd from rice consumption.

Numerous studies have reported that water management affects Cd (Bingham et al. 1976; Kikuchi et al. 2008) and As (Xu et al. 2008; Li et al. 2009; Hua et al. 2011; Somenahally et al. 2011; Spanu et al. 2012) bioavailability in soils and their subsequent uptake by rice. When a paddy field is flooded and the soil has a low redox potential, any Cd present in the soil combines with sulphur (S) to form CdS which has a low solubility in water (Bingham et al. 1976). Thus, flooding during the growing season, especially during later stages of plant growth, can effectively reduce Cd concentrations in rice gains (Arao et al. 2009). In contrast, anaerobic conditions in paddy soil lead to the reduction in arsenate to arsenite which enhances the bioavailability of As to rice plants (Masscheleyn et al. 1991; Marin et al. 1993; Takahashi et al. 2004). Thus, growing rice aerobically results in a marked decline in As accumulation in the rice (Xu et al. 2008; Li et al. 2009). Unfortunately, Cd and As are often co-contaminants in agricultural soils. It is therefore

necessary to investigate the feasibility of simultaneously mitigating both As and Cd accumulation in rice gains through water management.

Uptake of Cd and As has been shown to differ with rice cultivars (Morishita et al. 1987; Liu et al. 2005; Norton et al. 2009). Several studies have indicated that Cd uptake is significantly higher in Indica cultivars than in Japonica cultivars grown in Cd contaminated soils (He et al. 2006). Arsenic concentrations were found to be higher in hybrids than non-hybrids (Rahman et al. 2007; Dong et al. 2011). A high Cd translocation gene (qCdT7) has been identified in rice (Tezuka et al. 2010). Ahmed et al. (2011) reported that both genotype and environment influence As accumulation in rice grains. Therefore, selection and breeding of rice cultivars with low As and Cd accumulation have been considered to be reliable and achievable ways to reduce As and Cd in the rice grains in areas contaminated with both Cd and As (Zhang and Duan 2008).

In the present study, a field experiment was conducted to investigate the effects of four water management regimes on the accumulation of both As and Cd in seven major rice cultivars grown locally in Zhejiang province, east China. The main purpose was to achieve the optimum strategy for water management and local rice cultivar to alleviate As and Cd accumulation in the rice grains simultaneously and to achieve high yields.

Materials and methods

Site description and soil properties

The experimental site was located in a conventional agricultural field near Hangzhou city, Zhejiang province, east China. The soil belongs to the Typic Fe-leach-Stagnic Anthrosols (Gong 2007). The climate of the study area is moist monsoon with an annual precipitation of approximately 1,425 mm with the maximum during May and June and a mean temperature of 16 °C. Agriculture is the principal land use with a typical rotation system of rice from summer to autumn and wheat or rape from winter to the following spring. Soil pH (in H₂O) was 5.30, soil organic carbon content was 16.9 g kg⁻¹ and the cation exchange capacity (CEC) was 13.5 cmol (+) kg⁻¹. Soil total N, P and K were 1.46, 0.68 and 10.2 g kg⁻¹, respectively.

Soil available N, P and K were 95.2, 26.6 and 66.0 mg kg⁻¹, respectively. Soil total Zn, Cd, Cu and As were 147, 0.48, 26.0 and 6.49 mg kg⁻¹, respectively. The experimental soil was slightly contaminated with Cd according to the Chinese Environmental Quality Standard for Soils GB 1995–15618 (State Environmental Protection Administration of China 1995).

Field experiment

Seven major rice cultivars grown in Zhejiang province were used comprising two conventional Indica cultivars (Zhongxiang 1 and Indonesia, abbr. ZX1 and IR), three hybrid Indica cultivars (Liangyou Peijiu, Zhongzheyou 1 and Guodao 6, abbr. LYPJ, ZZY1 and GD6, respectively), one conventional Japonica cultivar (Xiushui 09, abbr. XS09) and one hybrid Japonica cultivar (Yongyou 9, abbr. YY9). The seeds of the seven cultivars were sown on May 28, 2010, and the seedlings were transplanted on June 21, 2010 with a distance between seedlings of 25 cm. All plots were flooded for 1 week after transplanting, and then, four water management regimes were applied. These were (1) aerobic, that is, the water was discharged to leave a water layer ~5 cm deep in the narrow ditch around the plot (about 10 cm lower than the rice field) to maintain aerobic conditions in the plot; (2) intermittent, irrigated intermittently with discharge to leave a water layer ~5 cm deep in the ditch around the plot; (3) conventional irrigation, kept flooded until the full tillering stage (August 16) followed by intermittent irrigation; (4) flooding, flooded throughout the rice growing season. A split plot design was used with water treatments in the main plots and plant cultivars in the sub-plots. There were three replicate plots of each treatment. Each plot was 24 m² in area and had a one-metre-wide buffer strip. The total volumes of irrigation water used were ~300, 3,702, 6,203 and 8,704 m³ ha⁻¹ in the aerobic, intermittent, conventional and flooded treatments, respectively. Rainfall was recorded (Supplementary Fig. S1) using an automatic rainfall recording instrument (WatchDog 2900ET Weather Station, Spectrum Technologies, Plainfield, IL), and the total rainfall was calculated to be 4,743 m³ ha⁻¹. As a result, the total volumes of irrigation water and rainfall over the whole crop growth period were 5,043, 8,445, 10,946 and 13,447 m³ ha⁻¹ in the aerobic, intermittent, conventional and flooded treatments, respectively.

Other management details were the same for all treatments. Basal nutrients consisted of 375 kg ha⁻¹ mixed fertilizer (N: P: K 15: 6.5: 12) was applied 1 day before transplanting. The first topdressing with 120 kg ha⁻¹ of urea (containing 46 % N) was applied on July 1 (10 days after transplanting), and the second topdressing was applied on July 7, comprising 150 kg ha⁻¹ of urea, 150 kg ha⁻¹ of mixed fertilizer and 120 kg ha⁻¹ of KCl (equivalent to 52 % K). All plants were harvested on October 16, 2010.

Sample collection and analysis

Rice plant samples and their corresponding fresh soil samples from the top 15 cm of the soil profile were collected from each plot at harvest. All the plant and soil samples were placed in an ice cooler and taken to the laboratory within 4 h. Soil properties were analysed by standard methods (Sparks et al. 1996). Soil total and available N were determined by Kjeldahl digestion and distillation. Soil total and available P were determined by digestion with H₂SO₄/HClO₄ and extraction with 0.1 M HCl, respectively. Solution P was analysed by the molybdenum blue method. Soil total and available K were determined by digestion with HCl–HNO₃ (4: 1, v/v) and extraction with 1 M NH₄OAc, respectively. Solution K was analysed by flame photometry (Model 6400-A, Shanghai Analytical Instrument Factory, Shanghai, China). Soil total cationic heavy metals were analysed by digestion of 0.25 g samples with 12 ml HCl–HNO₃ (4: 1, v/v). Soil total As was determined by digestion of 0.25 g samples with 10 ml HNO₃ and 2 ml H₂SO₄. Soil available As and Cd were determined by extraction of about 14 g fresh soil sample with 46 ml 0.1 M HCl. The fresh soil water contents were measured simultaneously. Plant samples were dried at low temperature (50 °C). Plant (straw, brown rice, husk) Cd was analysed by digestion of 0.5 g samples with a mixture of 6 ml HNO₃ and 4 ml HClO₄. Plant As was analysed by digestion of 0.2–0.3 g samples with 6 ml HNO₃ and 2 ml H₂O₂. Cationic heavy metals in solution were measured by flame atomic absorption spectrophotometry (Varian SpectrAA 220 FS, Varian, Palo Alto, CA) or by graphite furnace atomic absorption spectrophotometry (Varian SpectrAA 220Z, Varian, Palo Alto, CA). Arsenic in solution was measured by atomic fluorescence spectrometry (AFS-930, Beijing Jitian Instruments, China). Certified reference materials GBW07401 and GBW07603 (Institute of Geophysical

and Geochemical Exploration, Langfang, Hebei province, China) were used for quality control. All chemicals used were of analytical reagent grade, and the element concentrations measured in the reference materials were within the certified ranges. The soil N, P, K and total Cd and As results presented are based on air-dried soil weight, and soil available As and Cd results are based on oven-dried soil weight.

Statistical analysis

Statistical analysis was performed using the SPSS version 16.0 for Windows software package (SPSS Inc., Chicago, IL). Means were compared by analysis of variance (ANOVA) and Duncan's multiple range test at the 5 % level. Data are presented as mean \pm standard error (SE) ($n = 3$). The correlation between As and Cd in tissues was examined using Pearson's test at the 5 and 1 % levels of significance.

Results

Soil HCl-extractable As and Cd concentrations

The bioavailability of As and Cd in soils was determined by extraction with 0.1 M HCl at harvest (Table 1). Flooding and conventional irrigation had higher concentrations of HCl-extractable As but lower HCl-extractable Cd than aerobic and intermittent irrigation. The HCl-extractable As concentrations in soil varied 2.45–6.46 times, and Cd concentrations

varied 1.28–2.31 times among the various water regimes. It should be noted that at harvest, the intermittent treatment had low water content in the soil, but the conventional treatment retained a higher soil water content. Therefore, the HCl-extractable metals showed no significant difference between intermittent and aerobic treatments or between conventional and flooded treatments.

Plant As concentrations

Figures 1 and 2 show the plant As and Cd concentrations. The As concentrations in the straw, husk and brown rice were affected by the various water treatments (Fig. 1). Generally, As concentrations followed the order aerobic < intermittent < conventional < flooding. The aerobic treatment significantly decreased plant As accumulation compared to the flooded treatment. The order of As concentrations in different tissues was straw > husk > brown rice, regardless of water management or rice cultivar (Fig. 1). The variation in As concentration in straw was significantly greater than in brown rice. The straw As concentrations varied from 0.96 to 8.42 mg kg⁻¹, and the brown rice As concentrations ranged from 0.14 to 0.45 mg kg⁻¹. It was observed that in the aerobic treatment, the transfer factors of As, that is, the ratio of the concentration in brown rice to the concentration in straw, were higher than in the other water treatments for some cultivars such as ZX1, LYPJ, ZZY1, IR and GD6 (Fig. 3).

The As concentrations in rice tissues differed among the cultivars tested regardless of water

Table 1 Soil HCl-extractable As and Cd concentrations ($\mu\text{g kg}^{-1}$)

Water management	ZX1	IR	LYPJ	ZZY1	GD6	XS09	YY9
<i>As</i>							
Aerobic	23.9 \pm 5.6 b	28.0 \pm 21.8 c	22.7 \pm 3.4 b	26.4 \pm 1.6 b	31.4 \pm 3.0 b	22.3 \pm 0.7 b	48.9 \pm 9.9 c
Intermittent	23.6 \pm 3.6 b	31.4 \pm 17.4 c	29.5 \pm 7.2 b	30.4 \pm 7.7 b	36.8 \pm 18.4 b	28.5 \pm 6.0 b	34.9 \pm 9.7 c
Conventional	89.9 \pm 40.4 a	80.0 \pm 17.9 b	58.9 \pm 16.7 ab	41.1 \pm 7.3 b	79.8 \pm 26.7 a	137 \pm 4 a	113 \pm 22 b
Flooding	111 \pm 18 a	125 \pm 19 a	90.4 \pm 30.9 a	64.6 \pm 24.9 a	110 \pm 21 a	144 \pm 30 a	153 \pm 25 a
<i>Cd</i>							
Aerobic	272 \pm 13 a	304 \pm 32 a	284 \pm 17 a	343 \pm 45 a	230 \pm 72 ab	322 \pm 22 a	298 \pm 34 a
Intermittent	316 \pm 39 a	280 \pm 36 a	286 \pm 10 a	359 \pm 26 a	301 \pm 69 a	337 \pm 35 a	277 \pm 20 a
Conventional	173 \pm 22 b	123 \pm 88 b	252 \pm 27 a	240 \pm 45 b	240 \pm 19 ab	176 \pm 101 b	42 \pm 11 b
Flooding	169 \pm 73 b	139 \pm 101 b	221 \pm 72 a	167 \pm 44 b	130 \pm 60 b	162 \pm 67 b	33 \pm 0 b

Data are mean values \pm SE ($n = 3$). Data with the same letter in the same column and same metal indicate no significant difference at the 5 % level

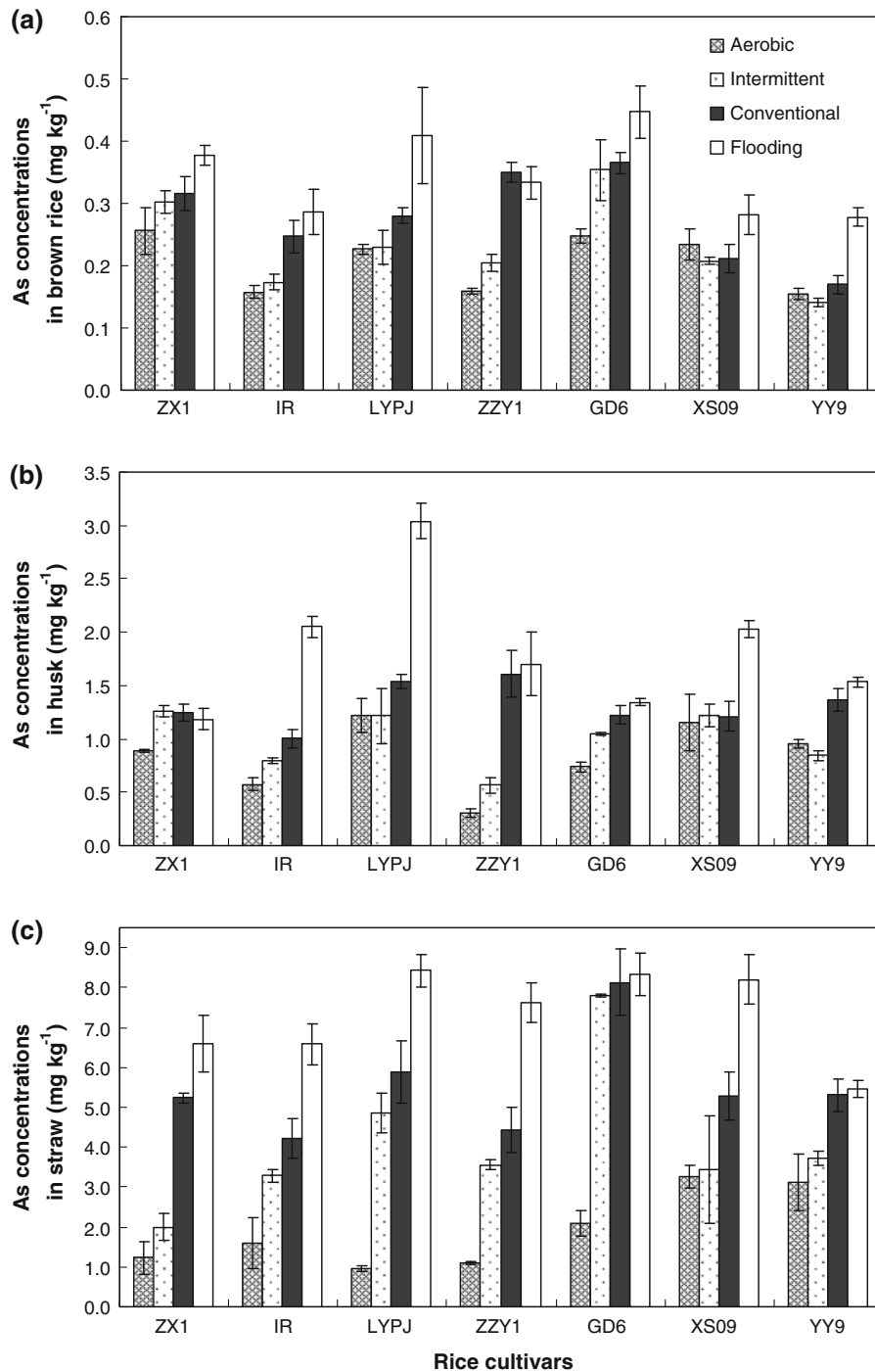


Fig. 1 Effects of water management regimes on As concentrations in the brown rice (a), husk (b) and straw (c) of different rice cultivars. The plotted columns are mean values \pm SE ($n = 3$)

treatments (Fig. 1). In straw, GD6 had relatively high As concentrations in the intermittent and conventional treatments and ZX1, LYPJ and ZZY1

had relatively low As concentrations in the aerobic treatment. GD6 had the highest brown rice total As concentrations, and IR and YY9 had the lowest As

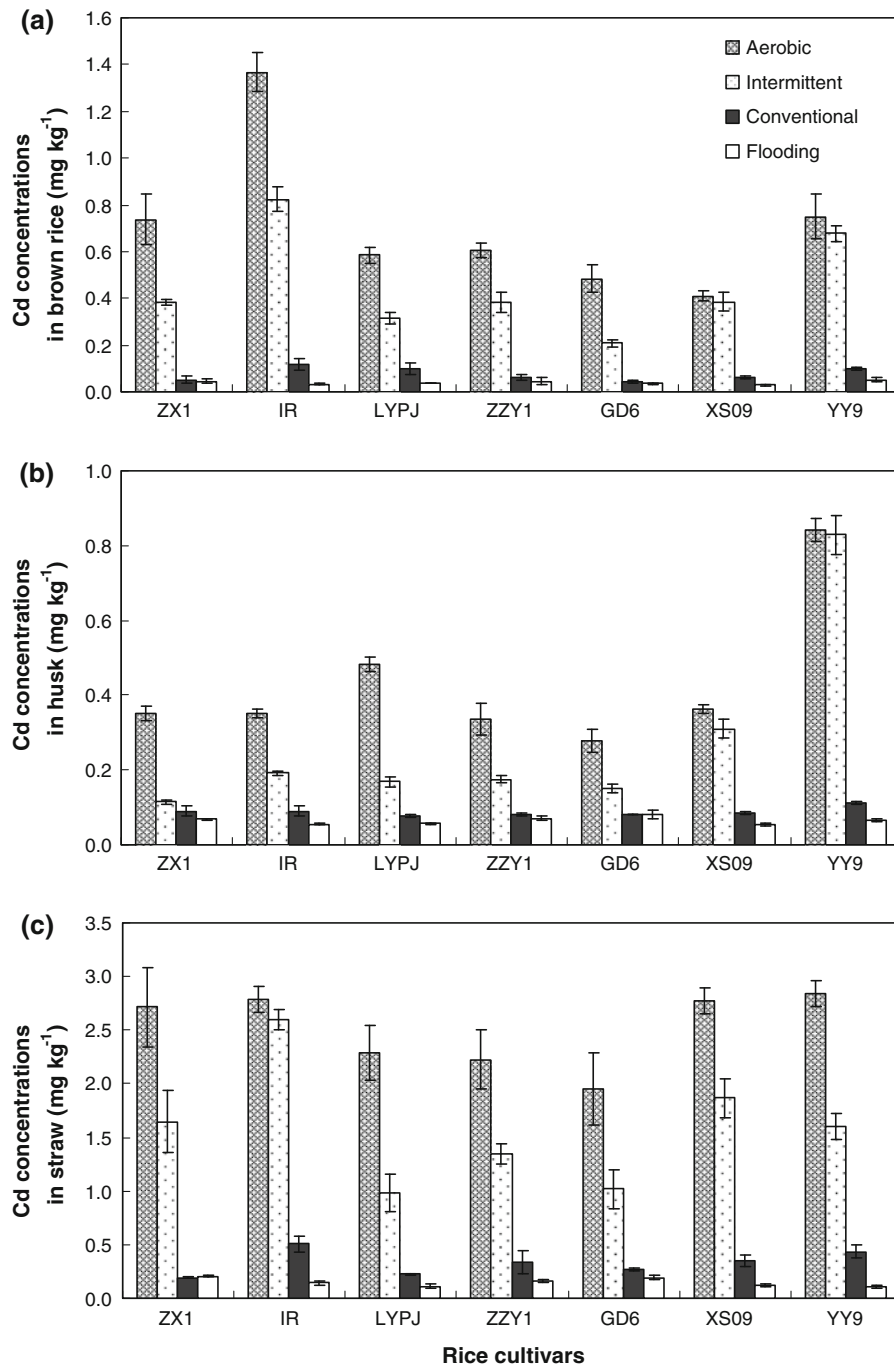


Fig. 2 Effects of water management regimes on Cd concentrations in the brown rice (a), husk (b) and straw (c) of different rice cultivars. The plotted columns are mean values \pm SE ($n = 3$)

concentrations regardless of water treatments. In the aerobic treatment, the As concentrations in brown rice of GD6 were 1.60 times higher than in YY9.

Plant Cd concentrations

Plant Cd concentrations were also largely affected by the different water treatments (Fig. 2). The order of

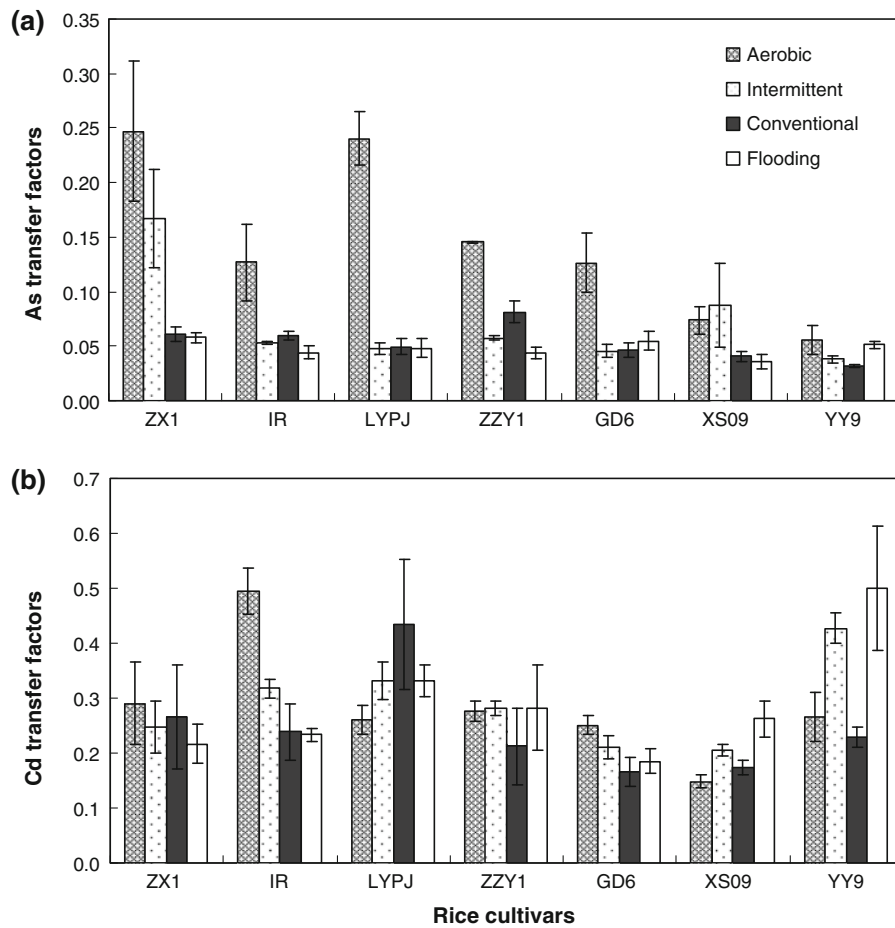


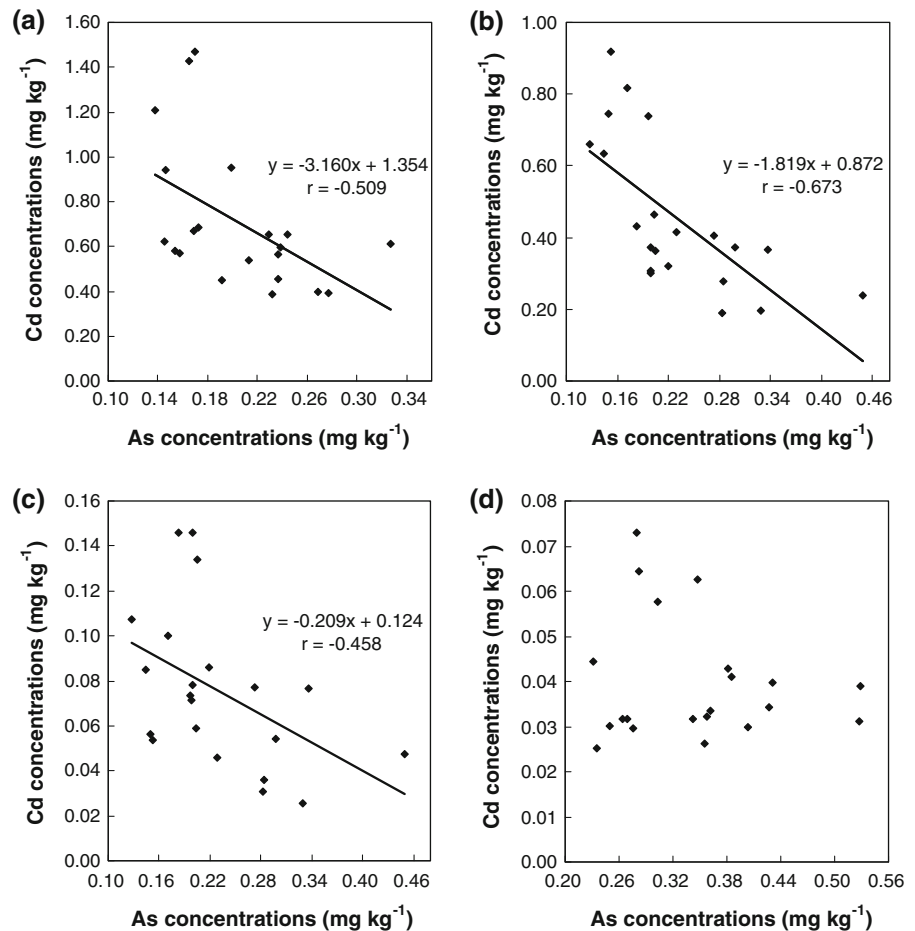
Fig. 3 Effects of water management regimes on transfer factors of As (a) and Cd (b) in different rice cultivars. The plotted columns are mean values \pm SE ($n = 3$)

total Cd concentrations among the four water management scenarios was aerobic > intermittent > conventional > flooding. The continuously flooded and conventional treatments greatly decreased the Cd concentrations in straw, husk and brown rice compared to the aerobic and intermittent treatments. For example, in IR, the brown rice Cd in the flooded treatment was 40.8 times lower than in the aerobic treatment. According to the Maximum Levels of Contaminants in Foods of China (GB 2762–2005) [Ministry of Health of China and Standardization Administration of China (2005)], Cd concentrations in milled rice should be $<0.2 \text{ mg kg}^{-1}$. The Cd concentrations in the brown rice of all 7 cultivars tested in the flooded treatment and conventional irrigation ranged from 0.03 to 0.12 mg kg^{-1} which was below the maximum Chinese level of 0.2 mg kg^{-1} . Although the

intermittent treatment decreased plant Cd accumulation compared to the aerobic treatment, Cd concentrations in the brown rice of the 7 cultivars still exceeded the maximum Chinese level.

In addition to water management, plant cultivars influence the plant Cd concentrations (Fig. 2). In the flooded treatment, Cd concentrations in the brown rice were very low ($0.03\text{--}0.05 \text{ mg kg}^{-1}$) and did not differ significantly among the cultivars. The Cd concentrations in the brown rice of IR under the aerobic and intermittent treatments reached 1.37 and 0.82 mg kg^{-1} which were notably higher than the other cultivars. Nevertheless, some cultivars such as XS09 and GD6 showed relatively low Cd accumulation in the brown rice, although they exceeded the maximum level of 0.2 mg kg^{-1} in the aerobic and intermittent treatments. Similar to brown rice, straw Cd in IR was the highest but

Fig. 4 Correlation analysis of brown rice As and Cd concentrations among different rice cultivars in aerobic (a), intermittent (b), conventional (c) and flooded (d) treatments



in GD6 was the lowest among the 7 cultivars. The transfer factors of Cd in XS09 and GD6 were lower than in the other cultivars regardless of water management (Fig. 3). Moreover, Pearson correlation analysis showed that the concentrations of As and Cd in the brown rice of all 7 rice cultivars were significantly negatively correlated in the aerobic ($r = -0.509$, $p < 0.05$), intermittent ($r = -0.673$, $p < 0.01$) and conventional ($r = -0.458$, $p < 0.05$) treatments (Fig. 4).

Rice yields

In all of the rice cultivars examined, the grain yields in the intermittent and conventional treatments were higher than in the aerobic and flooded treatments (Table 2). The super hybrid rice cultivar GD6 produced the highest grain yields. ZX1, a scented rice cultivar, gave lower yields. The local conventional

irrigation method was most suitable for the pattern of crop growth.

Discussion

In the present study, we investigated the effects of four different water management regimes on the As and Cd accumulation and yields of 7 rice cultivars under field conditions. It is known that the water regime affects heavy metal speciation in soils and consequently the plant availability. Compared to aerobic conditions, anaerobic conditions increase the mobilization of As in soils. This is due to the reduction in arsenate to arsenite which then desorbs from the adsorption surfaces of iron oxyhydroxides into the solution phase, and due to the reductive dissolution of iron oxyhydroxides which releases the adsorbed or co-precipitated As into the solution (Takahashi et al. 2004; Xu

Table 2 Rice grain yield of different cultivars (tonnes ha⁻¹)

Water management	ZX1	IR	LYPJ	ZZY1	GD6	XS09	YY9
Aerobic	7.74 ± 0.35 b	6.44 ± 0.45 b	11.5 ± 0.6 ab	8.41 ± 0.60 c	12.4 ± 0.5 a	7.84 ± 0.61 b	10.0 ± 0.8 a
Intermittent	9.95 ± 0.44 a	9.42 ± 0.69 a	12.8 ± 0.7 a	11.0 ± 0.7 a	13.0 ± 0.6 a	10.5 ± 0.7 a	11.0 ± 0.8 a
Conventional	10.0 ± 0.5 a	9.25 ± 0.47 a	12.9 ± 0.7 a	10.8 ± 0.5 a	13.1 ± 0.5 a	10.2 ± 0.7 a	10.9 ± 0.7 a
Flooding	7.89 ± 0.40 b	7.25 ± 0.44 b	11.1 ± 0.6 b	9.32 ± 0.67 b	11.4 ± 0.5 b	8.00 ± 0.58 b	9.79 ± 0.88 a

Data are mean values ± SE (n = 3). Data with the same letter in the same column indicate no significant difference at the 5 % level

et al. 2008; Yamaguchi et al. 2011). However, anaerobic conditions decrease the mobilization of Cd in soils due to the combining of Cd with sulphur (S) to form CdS at low redox potential (Bingham et al. 1976). In the present study, the water treatments exerted opposite effects on As and Cd availability in the soil (Table 1). HCl-extractable As concentrations in the flooded treatment were 2.45–6.46 times higher than in the aerobic treatment. HCl-extractable Cd concentrations in the flooded treatment were 1.28–2.31 times lower than in aerobic conditions. The effects of the intermittent and conventional treatments were intermediate between the aerobic and flooded treatments. Similarly, Xu et al. (2008) reported that during the period of active rice growth, the As concentration in the soil solution was 4–13 times higher under flooded than under aerobic conditions. Arao et al. (2009) also reported that Cd concentrations in the soil solution were below the detection limit during the time of flooding but increased during aerobic conditions.

Consistent with As and Cd bioavailability in soils, water management regimes exerted marked but opposite effects on Cd and As accumulation in the straw, husk and grains of the plants (Figs. 1, 2). The increasing amount of water during the growing season from aerobic to flooded treatments significantly decreased plant Cd accumulation but increased As accumulation. In the conventional treatment, flooding was changed to intermittent irrigation after the full tillering stage in order to decrease non-effective tillering (Hu and Ding 2008). Compared to the continuously flooded treatment, intermittent irrigation after full tillering in the conventional treatment decreased As concentrations but increased Cd accumulation in the grain. Compared to the intermittent treatment, the conventional treatment with flooding before full tillering increased As concentrations but

decreased Cd concentrations in the grains. This indicates that water management both before and after full tillering affected As and Cd accumulation in the grains. Similarly, in pot experiments, it has been reported that flooding 3 weeks before and after heading was most effective in reducing Cd concentrations in rice grains, while aerobic treatment for 3 weeks before and after heading effectively reduced As concentrations in the grains (Arao et al. 2009). Maintaining aerobic conditions during either the vegetative or reproductive stage of rice growth also decreased As accumulation in straw and grains significantly compared with rice grown under flooded conditions (Li et al. 2009). It is therefore difficult to simultaneously reduce As and Cd accumulation in rice by using water management alone in soils polluted with both As and Cd.

However, in the present field experiment, Cd concentrations in the brown rice and straw varied 13.1- to 40.8-fold and 10.0- to 20.2-fold, respectively, among the different water regimes, but the As concentrations in the straw and in brown rice varied 1.75- to 8.80-fold and 1.21- to 2.08-fold, respectively. Clearly, the response of plant Cd concentrations was more sensitive than As concentrations to water management. Compared to aerobic and intermittent irrigation, flooding and conventional irrigation significantly decreased Cd concentrations in the straw, husk and grains. Cd concentrations in the brown rice of conventional irrigation were 6- to 15-fold and 3- to 8-fold lower than in aerobic conditions and intermittent irrigation, respectively. Cd concentrations in the brown rice of all 7 cultivars in flooding and conventional irrigation were well below the Chinese maximum levels (milled rice Cd < 0.2 mg kg⁻¹) (GB 2762–2005). This indicates that if we consider Cd only, flooding and conventional irrigation methods can ensure the production of Cd safe rice regardless of

cultivar even in soil slightly polluted with Cd (0.48 mg kg^{-1}). However, in the case of As, flooding and conventional treatments produced higher concentrations in the plants compared to the aerobic and intermittent treatments (Fig. 1). On the other hand, our field study demonstrates that water regime significantly affects rice yields. The local conventional irrigation method and intermediate method were the most consistent with the pattern of crop growth, whereas continuous flooding and aerobic conditions were unsuitable for rice growth (Table 2). Thus, if we take both As and Cd as well as grain yields into account, conventional irrigation is the most efficient choice to control both metals in rice grain in the present soil conditions. In addition, it has been observed that for some cultivars, the transfer factors of As in aerobic conditions are higher than in other water treatments (Fig. 3), possibly due to a reduction in As uptake by the roots and/or changes in As species in the tissues affecting As translocation (Raab et al. 2007; Norton et al. 2010).

There have been reports that different rice cultivars show different behaviours in relation to the uptake and accumulation of Cd (Morishita et al. 1987; He et al. 2006; Yu et al. 2006) and As (Rahman et al. 2007; Norton et al. 2009; Pillai et al. 2010; Ahmed et al. 2011; Dong et al. 2011). However, few reports have considered As and Cd accumulation simultaneously in rice cultivars. In the present study, the brown rice Cd concentrations in the flooded treatment were very low ($0.03\text{--}0.05 \text{ mg kg}^{-1}$) and did not differ significantly among the 7 cultivars (Fig. 1). In the other three water treatments, the brown rice Cd concentrations in IR (conventional Indica) and YY9 (hybrid Japonica) were the highest. Cd concentrations in these two cultivars were 2.68- to 3.95-fold higher and 1.55- to 3.25-fold higher than the lowest GD6 (three-line hybrid Indica). Conversely, regardless of water management, the As concentration in the brown rice of GD6 was the highest, but the As concentration in the brown rice in IR and YY9 was the lowest among the 7 cultivars. Moreover, the concentrations of As and Cd in the brown rice of all 7 rice cultivars were significantly negatively correlated (Fig. 4). It seems that rice tends to accumulate either Cd or As. These results indicate that an antagonism might exist between As and Cd accumulation in rice grains (Sun et al. 2008). They also suggest that Cd and As should be considered together when screening rice cultivars for food safety.

Among the 7 cultivars used in the present study, YY9 had relatively low As concentrations in the brown rice as well as relatively low As transfer factors from straw to grains. Thus, YY9 can be considered to be a low-As-accumulating cultivar with potential for growing in As polluted fields with relatively aerobic irrigation. In contrast, GD6 had low Cd concentrations in the brown rice as well as low Cd transfer factors and might be a low-Cd-accumulating cultivar for Cd polluted fields with relatively anaerobic conditions. XS09 had low As and Cd transfer factors and accumulated neither high Cd nor high As in the brown rice, so it might be suitable for use in As and Cd co-polluted soils with conventional irrigation.

Conclusions

In the present field study, we investigated the effects of different water management regimes on As and Cd accumulation and yields of 7 rice cultivars. The results suggest that water management and rice cultivar dramatically affected As and Cd concentrations in rice grain but in opposite directions. Selecting proper water management measures and rice cultivars according to the degree of heavy metal pollution in soils will benefit food security as well as high yields. The present study suggests that the optimum strategies are to choose a low-Cd-accumulating cultivar such as GD6 with local conventional irrigation practice in Cd polluted paddy fields, a low-As-accumulating cultivar such as YY9 or IR with intermittent irrigation in As polluted paddy fields and a low-Cd-/As-accumulating cultivar such as XS09 with intermittent irrigation in Cd and As co-polluted paddy fields.

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