Effects of water management on Cd and As content in rice grain

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Abstract
Rice consumption is a major source of cadmium and arsenic for the population of Asia. We investigated the effects of water management in rice paddy on levels of cadmium and arsenic in Japanese rice grains. Flooding increased arsenic concentrations in rice grains, whereas aerobic treatment increased the concentration of cadmium. Flooding for three weeks before and after heading was most effective in reducing grain cadmium concentrations, but this treatment increased the arsenic concentration considerably, whereas aerobic treatment during the same period was effective in reducing arsenic concentrations but increased the cadmium concentration markedly. Flooding treatment after heading was found to be more effective than flooding treatment before heading in reducing rice grain cadmium without a concomitant increase in total arsenic levels.

Key Words
Codex Alimentarius Commission, JECFA, pot experiments, PTWI, redox potential, soil solution.

Introduction
Cadmium (Cd) is toxic to humans at concentrations lower than those at which it is toxic to plants, because its effects on humans are cumulative (Singh and McLaughlin 1999). Soil pollution by Cd has been of public concern since the 1970s, when it was discovered that daily ingestion of rice (*Oryza sativa* L.) containing high levels of Cd is the main cause of itai-itai disease (Kobayashi 1978). A health-based guidance value for Cd of 7 µg/kg bodyweight per week [the provisional tolerable weekly intake (PTWI)] has been established by the Joint Expert Committee on Food Additives (JECFA) of the Food and Agriculture Organization and the World Health Organization. Recently, the European Food Safety Authority established a tolerable weekly intake for Cd of 2.5 µg/kg body weight. The weekly intake of Cd from foods in Japan in 2001 was estimated to be 4.1µg/kg body weight, and about half the Cd intake from foods was from rice. A re-evaluation of Cd is scheduled for the 2010 meeting of the JECFA. A maximum concentration of 0.4 mg/kg for Cd in white rice grain has been adopted by the Codex Alimentarius Commission. Rice is a staple crop in Asia, and is the principal source of dietary intake of Cd in the Japanese population; therefore, minimizing the intake of Cd from rice is an important health issue.

Arsenic (As) is a carcinogen and the intake of inorganic As in rice is a significant risk factor for cancer in populations for whom rice is a staple foodstuff (Mondal and Polya 2008). In some cases, human As intake from the consumption of rice exceeds that from drinking water (Williams *et al.* 2006). For inorganic As, a PTWI of 15 µg/kg body weight has been established by the JECFA. The Ministry of Agriculture, Forestry, and Fisheries of Japan analyzed the As contents of staple crops in Japan and found that As concentrations in brown rice ranged from 0.04 to 0.33 mg/kg, with an average value of 0.16 mg/kg (n = 199); the average values for wheat, soybean, and spinach were 0.008, 0.005, and 0.010 mg/kg, respectively. Rice is therefore a major source of dietary intake of inorganic As in the Japanese population. Contamination by As occurs to a greater extent in paddy rice than in other upland crops because anaerobic conditions in paddy soil lead to arsenic mobilization and thus enhanced bioavailability to rice (Takahashi *et al.* 2004).

Flooding of paddy fields is effective in reducing grain levels of Cd; however, anaerobic conditions in paddy soil lead to arsenic mobilization and, therefore, As uptake by rice could increase (Koyama, 1975, Kyuma, 2004). The main objective of the present study was to investigate the simultaneous effects on Cd and As levels in rice grains induced by water management of paddy soil before and after emergence of the rice ears.

Methods
Pot experiments, with three or six (treatment 1) replications each, were performed in 2008 in a greenhouse at ambient temperatures (7–36 °C) under sunlight. Wagner pots (1/5000 a, Fujiwara Scientific Co., Tokyo, Japan) were filled with 3 kg of two kinds of soil collected from the plow layer of paddy fields. Soil A

contained 1.6% total C, 0.15% total N, 0.56 mg/kg total Cd, and 25 mg/kg total As, and it had a pH of 5.6. Soil B contained 3.4% total C, 0.32% total N, 0.66 mg/kg total Cd, and 48 mg/kg total As, and it had a pH of 5.5. Eh was measured at a depth of 10 cm. A soil-water sampler (DIK8393, Daiki Rika Kogyo Co., Saitama, Japan) was buried in the middle of the soil of each pot for collecting soil solution. The soil solution was sampled 33, 54, 70, 83, and 90 days after transplanting and diluted with 10% HNO_3 at a ratio of 9:1 immediately after collection and filtered through a sterilized 0.45-µm filter. Seedlings of rice (*O. sativa* L. cv. Koshihikari) were germinated on perlite and transplanted into the soil samples on 14 May 2008. A compound fertilizer containing 0.2 g of N, 0.04 g of P, and 0.08 g of K was supplied to each pot by basal application. Ammonium sulfate containing 0.2 g of N was also supplied to each pot by top dressing 60 days after transplantation of the rice seedlings.

Seven water-management treatments were examined in the experiment: treatment 1 involved flooding throughout the entire growth period; treatment 2, flooding from transplanting to three weeks after heading; treatment 3, flooding from transplanting to heading; treatment 4, flooding from transplanting to three weeks before heading and from heading to three weeks after heading; treatment 5: flooding from transplanting to three weeks before heading; treatment 6, flooding from transplanting for two weeks and then from three weeks before heading to three weeks after heading; and treatment 7, flooding from transplanting for two weeks. The heading days occurred between August 1st and August 6th. Water management was changed at the beginning of the last heading day of each treatment of the pot experiments. At the time of heading in treatment 1, the stems of the plants grown in three pots were cut 2 cm above the soil surface and the xylem sap that exuded from the cut surface was collected by trapping in a 1.5-mL plastic vial containing a small piece of cotton for 2 h after cutting the shoots. After the seeds had matured, the plants were cut off at the stem above the point at which they were immersed in water.

Results

Yields of rice grain and straw were significantly different for the various water treatments, and were highest for the continuous flooding treatment 1 and lowest for the aerobic treatment 7. In both the soils, rice from the continuous flooding treatment 1 had the lowest Cd concentration and the highest As concentration in grain (Table 1). Rice from treatment 5 had the highest Cd concentration in grain in soil A, and rice from treatments 5 and 7 had higher Cd concentrations in grain than rice from other treatments in soil B; rice grains from treatments 5 and 7 also had the lowest As concentration in both. The As concentrations in grain were significantly different between treatment 1 and treatment 2 in both soils. In both soils, rice grain from treatment 6, where flooded conditions existed between 3 weeks before heading and 3 weeks after heading, had a higher concentration of As and a lower concentration of Cd than rice grain from treatments 3, 4, 5, and 7. Rice grain from treatment 4 had a 59–62% lower Cd concentration than that from treatment 3 in both soils; however, the As concentrations in the rice grains were not significantly different between treatments 3 and 4 in both soils.

In soils A and B, rice straw from the continuous flooding treatments 1 and 2 had a higher As concentration and a lower Cd concentration than rice straw from other treatments (Table 1). Rice straw from treatment 4 had a significantly lower Cd concentration than rice straw from treatment 3 in both soils. Rice straw from treatment 4 also had a significantly lower As concentration than rice straw from treatment 3 in soil A. Rice straw from the aerobic treatment 7 had the lowest As concentration in both soils. Flooding treatment

Table 1. Effects of water management on As speciation and Cd concentration in grain and straw.

	grain				straw			
	Soil A		Soil B		Soil A		Soil B	
	As	Cd	As	Cd	As	Cd	As	Cd
Water management	mg kg^{-1}				mg kg^{-1}			
1	0.95 ± 0.044 a	0.005 ± 0.001 a	1.7 ± 0.118 a	0.010 ± 0.003 a	27.3 ± 0.66 b	0.02 ± 0.004 a	26.2 ± 0.85 a	0.03 ± 0.004 a
2	0.92 ± 0.029 a	0.016 ± 0.002 a	1.7 ± 0.077 a	0.046 ± 0.011 b	29.5 ± 0.29 a	0.14 ± 0.014 a	26.7 ± 0.27 a	0.22 ± 0.054 a
3	0.30 ± 0.020 c	0.36 ± 0.003 d	0.59 ± 0.014 c	0.27 ± 0.012 d	15.9 ± 0.59 d	1.4 ± 0.043 d	17.0 ± 0.76 c	1.3 ± 0.093 c
4	0.36 ± 0.007 c	0.21 ± 0.018 b	0.60 ± 0.037 c	0.16 ± 0.011 c	11.7 ± 0.70 e	1.1 ± 0.10 c	18.1 ± 0.57 c	0.85 ± 0.097 b
5	0.11 ± 0.026 d	0.41 ± 0.034 e	0.17 ± 0.030 d	0.34 ± 0.020 e	1.8 ± 0.09 f	2.0 ± 0.14 e	5.0 ± 0.18 d	1.3 ± 0.051 c
6	0.55 ± 0.006 b	0.066 ± 0.006 a	1.26 ± 0.044 b	0.063 ± 0.006 b	18.4 ± 0.84 c	0.66 ± 0.12 b	23.2 ± 0.64 b	0.57 ± 0.013 b
7	0.10 ± 0.014 d	0.28 ± 0.021 c	0.14 ± 0.027 d	0.38 ± 0.011 e	1.1 ± 0.53 f	1.4 ± 0.10 d	0.9 ± 0.22 e	2.4 ± 0.24 d

The same letters are not significant at the 5% level.

increased the concentration of As in rice grain and straw, whereas aerobic treatment increased the concentration of Cd in rice grain and straw (Table 1). This occurs because flooding decreases the redox potential of the soil and increases the As concentration in the soil solution, whereas aerobic treatment increases the redox potential of the soil and increases the Cd concentration in the soil solution (Figure 1). For reducing the Cd concentration in grain, flooding three weeks before and after heading (treatments 1, 2, and 6) was most effective; however, the As concentration in grain increased considerably as a result. On the other hand, for reducing the As concentration in grain, aerobic treatment for three weeks before and after heading (treatments 5 and 7) was most effective, but the concentration of Cd in the grain increased considerably as a result.

Flooding for three weeks after heading was more effective in reducing Cd concentrations in grain than was flooding for three weeks before heading (Table 1); the effects on the As concentration in grain were similar for flooding three weeks after heading and for flooding for three weeks before heading. The value of Eh

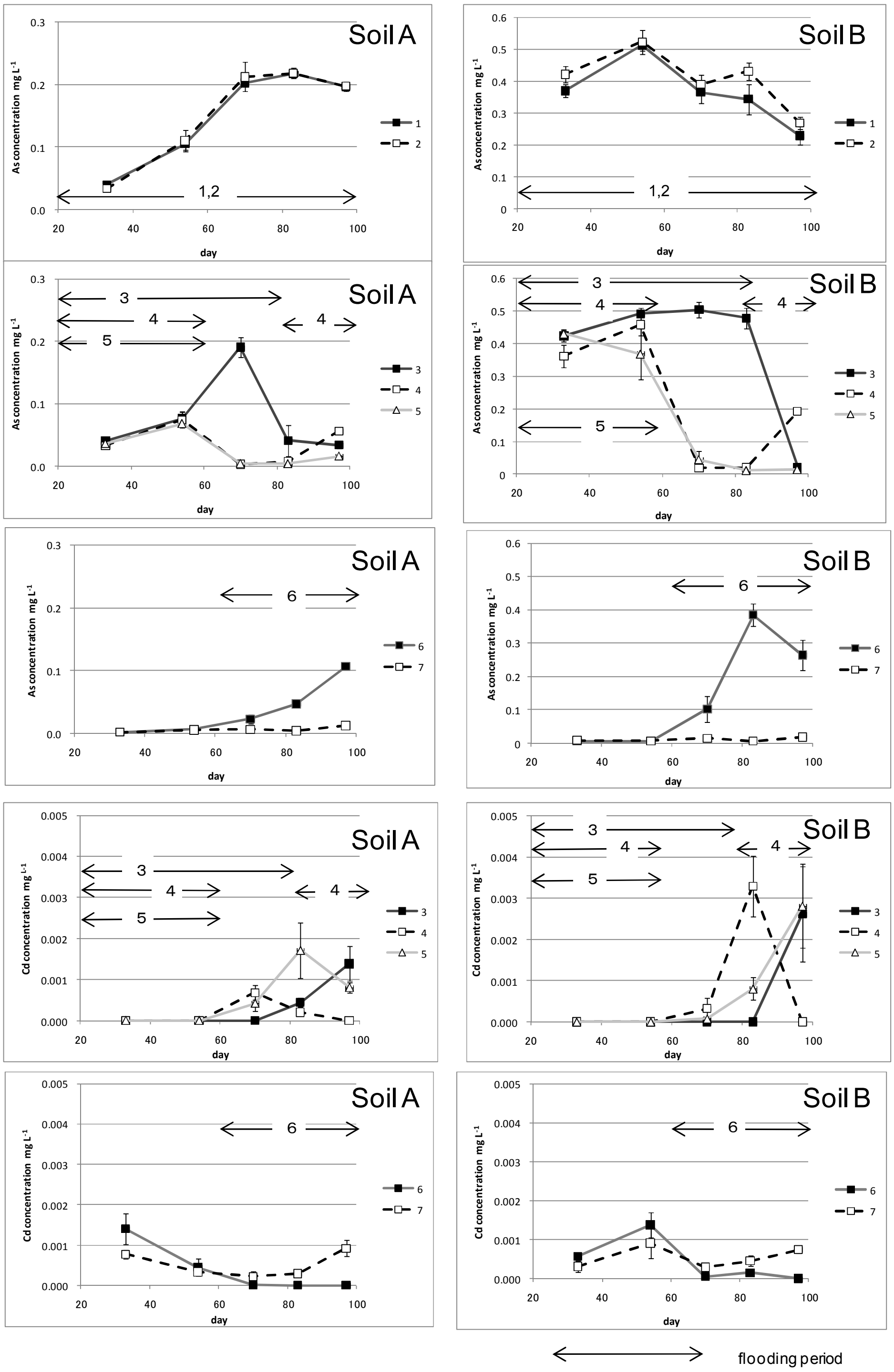

Figure 1. Effects of water management on As and Cd concentrations in soil solution.

increased to above 0 mV immediately after aerobic treatment in treatment 3, and the Cd concentrations in the soil solutions of both soils on day 97 in treatment 4 were below detectable limits (Figure 1). However, the value of Eh gradually decreased and fell below –200 mV about 100 days after flooding in treatment 4. Therefore, the uptake of Cd by rice from the soil solution should increase immediately after the aerobic treatment of treatment 3, and the uptake of As by rice from the soil solution should not increase immediately after the flooding treatment of treatment 4. The effect of flooding treatment after heading on the accumulation of Cd by rice grain should be greater than that on accumulation of As.

Levels of inorganic As in grain were much higher in treatment 4 than in treatment 5 or treatment 3. Therefore, flooding after heading should produce a greater increase in inorganic As levels than flooding before heading. Because As accumulation in grain should be greater after heading than before heading, flooding after heading should lead to arsenic mobilization in soil and thus grain levels of inorganic As should increase. Another possibility is that the relocation of As from the leaves increases. Grain As concentrations in treatments 5 and 7 were almost the same (Table 1), so flooding until 52 days after transplanting did not affect the grain As concentrations when rice was grown in aerobic conditions after day 52. The grain As concentrations in treatment 1 were 1.2-fold higher than those in treatment 2 in both soils, whereas grain Cd concentrations in treatment 2 were 2.3- and 4.7-fold higher than in treatment 1 in soil A and soil B, respectively (Table 1). Therefore, water management just before harvesting time should have a greater impact on the Cd concentration in grain than on the As concentration.

The same water-management regime could cause different changes in the redox potentials for various types of soils because of differences in the properties of the soils, such as aggregate development. It may therefore be difficult to maintain low Cd and As concentrations in grain simultaneously by means of water management alone. Silicon fertilization decreases As and Cd concentrations in rice grain (Inahara *et al.* 2007; Li *et al.* 2009), so it will be necessary to screen for more materials that could reduce As and/or Cd concentrations in rice grain. Some tropical japonica cultivars with low levels of As in their grains have the potential to be used in breeding (Norton *et al.* 2009).

Conclusion

In conclusion, our study showed that water management before and after the heading time is important in managing the Cd and As concentrations simultaneously in rice grain.

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