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Application of a rotation system to oilseed rape and rice fields in Cd-contaminated agricultural land to ensure food safety

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ABSTRACT

This field experiment analyzed the phytoremediation effects of oilseed rape in moderately cadmium (Cd)-contaminated farmland and the food safety of successive rice in an oilseed rape-rice rotation system. Two oilseed rape cultivars accumulated Cd at different rates. The rapeseed cultivar Zhucang Huazi exhibited high Cd accumulation rates, higher than the legal limit for human consumption (0.2 mg kg^{-1}); Cd concentrations in the cultivar Chuanyou II-93 were all below the maximum allowed level. Planting oilseed rape increased the uptake of Cd by the successive rice crop compared with a previous fallow treatment. Most Cd concentrations of brown rice were below the maximum allowed level. The phytoextraction efficiency was lower in the moderately Cd-contaminated soil in field experiments. The results suggest screening rice cultivars with lower Cd accumulation can assure the food safety; the mobilization of heavy metals by roots of different plant species should be considered during crop rotation to assure food safety.

1. Introduction

Currently, people pay increased attention to food safety because of increasing environmental contamination. Cd, a non-essential element that is toxic to plants, has no known physiological function (Wang et al., 2007). Because cadmium (Cd) has high mobility, plants readily absorb and accumulate it, posing a severe risk to food safety and human health (Moreno-Caselles et al., 2000; Nakadaira and Nishi, 2003; Yang et al., 2004). Cd can enter the food chain via plant uptake from contaminated soils, which are the major source of Cd exposure for humans (Kobayashi et al., 2002; Watanabe et al., 1998). Soils may be contaminated with Cd as a municipal or industrial waste, and Cd may be found in sewage sludge used for agricultural purposes, sewage used for irrigation, as a by-product of phosphate fertilizers and Cd may enter soils through atmospheric deposition (Chen et al., 2000; Khan et al., 2000; Liu et al., 2007; Tiller et al., 1997; Wong et al., 2002). These major sources of Cd in the environment may allow Cd to accumulate through the food chain especially in the suburbs near sources of Cd contamination.

China has undergone rapid industrialization and modernization over the last two decades, causing increasingly serious heavy metal contamination. In recent years, great strides have been made in remediation of contaminated soils using various techniques (Liu et al., 2009; Reddy and Chirakkara, 2013). However, many of these technological solutions are expensive, require long-term treatment, cause damage to soil structure or generate secondary contamination; in some cases these methods are impractical in Cd contaminated soils (Khan et al., 2000; Liu et al., 2009). Phytoremediation with hyperaccumulators of heavy metals is an effective, low cost, and in situ method of removing heavy metals from contaminated soils which would be a better alternative substituted for conventional remediation methods (Baker et al., 1994; Salt et al., 1998; Wu et al., 2011). Because China has limited land resources and large numbers of people, removing land from cultivation for extended periods of time for the purpose of remediation of moderately Cd-contaminated agricultural land is difficult and impractical. Therefore, land must be used efficiently and safely to meet the increasing demands for food.

Intercropping and crop rotation allows full use of light, heat, water and soil resources which is the essence of China traditional agriculture; these techniques have made significant contributions to sustainable crop production (Agegnehu et al., 2006; Daellenbach et al., 2005; Wei et al., 2010). Murakami et al. (2008, 2009) revealed that phytoextraction by a high-Cd-accumulating rice cultivar could reduce the seed level of Cd found in successive soybeans and rice grown on paddy soils contaminated with moderate levels of Cd. Keller and

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Hammer (2004) also reported that continuous cropping with *Thlaspi caerulescens* reduced Cd and Zn availability and toxicity. Our previous studies also showed that rotating crops with a high-Cd-accumulating oilseed rape could reduce the Cd content of vegetable Chinese cabbage and rice grown subsequently after oilseed rape (Su et al., 2010; Wu et al., 2011). Oilseed rape is widely grown in China and has higher Cd accumulation than other crops (Su and Wong, 2004). More than half of the world population use rice as their dominant staple food source. Also, rotation of oilseed rape and rice is a very common farming system in southern China.

However, most studies have used pot-based experiments. Will the same results be observed under field conditions? The objective of this study was to investigate the food safety of a successive rice crop in an oilseed rape and rice rotation system under field conditions. We attempted to establish a suitable rotation system in a Cd-contaminated soil to reduce the risk from Cd contamination, and evaluated the potential for removing Cd from the soil.

2. Materials and methods

2.1. Description of field experimental site

A field experiment was conducted from October 2008 to November 2010 in a paddy field with an alluvial loam soil, located on the outskirts of Fuyang County, Zhejiang Province, in eastern China (29°56.378′N–119°55.656′E). The subtropical monsoon climate receive an average of 1400 mm of rainfall annually; the average temperature is 16.1 °C. The paddy field used in this study lies adjacent to a copper refinery. The primary source of Cd contamination appeared to have been the heavy metal emissions from the nearby refinery. Some physical and chemical properties of the soil were: pH (H_2O), 7.76; organic matter, 39.59 g kg^{-1}; total N, 2.36 g kg^{-1}; available P, 33.38 mg kg^{-1}; and, available K, 76.38 mg kg^{-1}. Total and DTPA-extractable Cd were 0.96 and 0.69 mg kg^{-1}, respectively, in the soil 0–20 cm deep. According to Chinese Grade II environmental quality standard for soils (SEPA, 1995), the Cd limit for soils used for crop production is 0.6 for pH > 7.5. Thus, the concentration of Cd at the experimental site represents low to moderate levels of contamination.

2.2. Experimental arrangement

A common, local rotation system of oilseed rape (*Brassica juncea* L.) and rice (*Oryza sativa* L.) was used in the field experiment. Two varieties of oilseed rape, Zhucang Huazi (ZC) and Chuanyou II-93 (CY), were used throughout the experiment. Our previous studies have revealed that Zhucang Huazi has the ability to substantially accumulate Cd from contaminated soils, while Chuanyou II-93 showed the lower ability to accumulate Cd (Ru et al., 2004; Su and Wong, 2004). In the first year, the selected rice cultivar was Xiushui 113 with lower accumulation of Cd, while in the second year, a common cultivar, Zhejing 22, was grown.

The three treatments consisted of (1) the control (CK, no planting of oilseed rape and planting of rice), (2) the rotation of Zhucang Huazi with rice, and (3) the rotation of Chuanyou II-93 with rice. All 3.8 × 3.5 m^2 plots were arranged in a completely randomized design with three replicates per treatment. Seeds of Zhucang Huazi and Chuanyou II-93 were sown in October of 2008, and the seedlings were then transplanted into the plots in November with a planting density of 16 plants m^{-2}. After transplanting, basal fertilizers were applied at a rate of 70 kg N ha^{-1} in the form of urea and 9 kg ha^{-1} of boron fertilizer. Additional fertilizers were applied at a rate of 376 kg ha^{-1} of a mixed fertilizer and 88 kg N ha^{-1} in the form of urea in December and in January 2009, respectively. Pesticides were sprayed during the growth of the oilseed rape when necessary as a conventional practice. The oilseed rapes were harvested at maturity in May 2009. After the oilseed rapes were harvested, all the plots were submerged in water to prepare for rice cultivation. The Xiushui 113 rice seedlings were transplanted into the plots in June 2009. Then basal fertilizer was supplied at a rate of 123 kg N ha^{-1} in the form of urea in July. Additional fertilizers were supplied at a rate of 70 kg N ha^{-1} in the form of urea and 376 kg ha^{-1} in the form of a mixed fertilizer. Pesticides were sprayed during the growth of rice when necessary. The rice was harvested at maturity in September 2009.

In the second year, 2009, the oilseed rapes of Zhucang Huazi and Chuanyou II-93 were cultivated in the same plots as in 2008. A local rice cultivar, Zhejing 22, was selected in the second year to determine the food safety of common rice. The same farming practice of oilseed rape and rice was used as in the previous experiment.

2.3. Plant sampling and analysis

Grain, herbaceous parts (straw) and roots of oilseed rape and rice were collected from the field experiment as follows: six randomly selected oilseed rape plants and twenty rice plants per plot were taken just before the harvest in May and October, respectively. The collected plants were separated into shoots and roots. Shoots and roots were washed thoroughly with tap water, rinsed with deionized water, and dried at 70 °C for 48 h. After dried, the dry matter weights were recorded. Shoots were then threshed to separate the grain from the straw/chaff and the two components weighed again. Oven-dried plant materials were ground using a stainless steel mill. Subsamples of the ground materials were digested with ultra-pure HNO_3 (5 ml) and 30 percent H_2O_2 (2 ml) using a microwave (Mars-5, CEM Corp., USA) and the total Cd concentration was determined using an ICP-MS (ICP-MS 7700, Agilent Technologies, Santa Clara, CA, USA). For quality assurance, blank and a certified reference material (GSBZ5 1001-94-ESP-1, tomato leaf) were included in each batch with the recovery rate of 90–105 percent.

2.4. Soil sampling and analysis

Rhizosphere and non-rhizosphere soil samples were collected, together with plants at harvest from each plot. Rhizosphere soil (root system) was removed by shaking the plant roots gently. Meanwhile, five soil cores of non-rhizosphere soil (0–20 cm depth) were taken from the same site in an S shape. The samples from each plot were mixed and combined to provide a single sample. The collected soils were placed in plastic bags and transported immediately to the laboratory for analysis. Soil samples were air-dried at room temperature. Stones and roots were removed and air-dried soils were passed through a 1-mm mesh sieve for the analysis of soil characteristics. A portion of the soil samples was finely ground (< 0.15 mm) for the analysis of total Cd concentration. Soil pH was measured in a 1:2.5 (w/v) ratio of soil to deionized water using a pH meter. Available Cd was determined using a diethylenetriaminepentaacetic acid (DTPA) extraction (0.005 M DTPA + 0.01 M $CaCl_2$ + 0.1 M triethanolamine (TEA), pH = 7.3, solution: soil = 2:1, extraction for 2 h (Baker and Amacher, 1982). Total soil Cd concentration was determined using an aqua regia digest in the microwave followed by ICP-MS. Blanks and a certified reference material (GSBZ 50014-88) were included for quality assurance with a recovery rate of 95–110 percent.

2.5. Statistical analysis

All data were analyzed using SAS statistical package (SAS System for Windows, Version 8.02, SAS Institute Inc. Cary, NC, USA). All results are presented as arithmetic means with standard errors. Univariate analysis of variance were applied. Duncan's multiple range test was used at $P = 0.05$.

3. Results

3.1. Plant growth and Cd uptake by oilseed rape

Table 1 shows the dry matter weight, Cd uptake and phytoextraction efficiency of the two oilseed rape cultivars. The straw dry matter weights of Zhucang Huazi were 9.9 and 3.4 percent higher than Chuanyou II-93 in 2009 and 2010, respectively. The rapeseed yields of Zhucang Huazi were 0.9 and 3.6 percent higher than Chuanyou II-93 in 2009 and 2010, respectively. However, the dry matter weights of straw and rapeseed were not significantly different between the two oilseed rape cultivars both in 2009 and 2010. No symptoms of Cd toxicity were found in plants.

The accumulation of Cd differed significantly in the two oilseed rape cultivars (Table 1). The Zhucang Huazi cultivar absorbed more Cd from the soil than Chuanyou II-93. The total Cd uptake by cultivar of Zhucang Huazi were 1.58 to 1.76 times that of Chuanyou II-93 in 2009 and 2010, respectively. The phytoextraction efficiencies of Zhucang Huazi and Chuanyou II-93 ranged from 0.09 to 0.13 percent and 0.06 to 0.08 percent in 2009 and 2010, respectively, with that of Zhucang Huazi were 50 and 63 percent higher than Chuanyou II-93, respectively.

Analysis of the Cd concentrations in rapeseed and straw revealed significant differences between the two cultivars of oilseed rape at harvest in 2009 and 2010 (Fig. 1). Zhucang Huazi had a stronger ability to accumulate Cd than Chuanyou II-93.