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Predicting Cadmium Safety Thresholds in Soils Based on Cadmium Uptake by Chinese Cabbage

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ABSTRACT

Cadmium (Cd), a common toxic heavy metal in soil, has relatively high bioavailability, which seriously threatens agricultural products. In this study, 8 different soils with contrasting soil properties were collected from different regions in China to investigate the Cd transfer coefficient from soil to Chinese cabbage (*Brassica chinensis* L.) and the threshold levels of Cd in soils for production of Chinese cabbage according to the food safety standard for Cd. Exogenous Cd (0–4 mg kg^{-1}) was added to the soils and equilibrated for 2 weeks before Chinese cabbage was grown under greenhouse conditions. The influence of soil properties on the relationship between soil and cabbage Cd concentrations was investigated. The results showed that Cd concentration in the edible part of Chinese cabbage increased linearly with soil Cd concentration in 5 soils, but showed a curvilinear pattern with a plateau at the highest dose of exogenous Cd in the other 3 soils. The Cd transfer coefficient from soil to plant varied significantly among the different soils and decreased with increasing soil pH from 4.7 to 7.5. However, further increase in soil pH to > 8.0 resulted in a significant decrease in the Cd transfer coefficient. According to the measured Cd transfer coefficient and by reference to the National Food Safety Standards of China, the safety threshold of Cd concentration in soil was predicted to be between 0.12 and 1.7 mg kg^{-1} for the tested soils. The predicted threshold values were higher than the current soil quality standard for Cd in 5 soils, but lower than the standard in the other 3 soils. Regression analysis showed a significant positive relationship between the predicted soil Cd safety threshold value and soil pH in combination with soil organic matter or clay content.

Key Words: clay content, soil pH, soil organic matter, soil quality standard, transfer coefficient

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INTRODUCTION

Cadmium (Cd) is a common toxic heavy metal in the soil environment. Its relatively high bioavailability in soil means that it can be absorbed and accumulated by crop plants easily, which seriously threatens the quality and safety of agricultural products (Gong and Pan, 2006; Bolan *et al.*, 2013; Zhao *et al.*, 2015). Chronic exposure to Cd through various pathways including the dietary Cd intake can cause serious health hazards (Karalliedde and Brooke, 2012). Itai-itai disease, which was prevalent in the Jinzu River basin of the Toyama Prefecture of Japan during the 1930s and 1940s, was caused by consumption of Cd-contaminated rice produced from Cd-contaminated farmland (Nogawa *et al.*, 2004). Recently, there has been much public concern on the problem of Cd contamination in Chinese agricultural land (Zhao *et al.*, 2015). According to the national survey (MEP MLR, 2014), 19.4% of the soil samples from agricultural land in China exceed the national soil quality standards for one or more inorganic or organic contaminants. The main contaminants are heavy metals or metalloids, accounting for 82% of the total contaminated soils, among which Cd ranks the first with 7% of soil samples exceeding the soil quality standard. Mining is one of the main factors causing soil Cd contamination. In southern and southwestern areas of China such as Yunnan, Guangdong, Hunan and Guizhou, which are rich in metallic mineral resources, soil Cd pollution caused by mining and smelting is particularly serious. A number of studies showed that the edible parts of vegeta-

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bles, such as sweet potato, cabbage, pepper, eggplant, cucumber and spinach, grown in mining-impacted soils frequently exceeded the Chinese food safety standards for Cd (0.2, 0.1 and 0.05 mg kg^{-1} fresh weight for the leafy, rootstalk and other vegetables, respectively). Recent surveys in some areas along the Xiang River basin in Hunan, China showed that large proportions (60%–76%) of rice grain exceeded the 0.2 mg kg^{-1} Cd limit in rice (Du *et al.*, 2013; Zhu *et al.*, 2016).

Vegetables are a main source of Cd ingestion by humans (Clemens *et al.*, 2013). Because of the differences in genetic characteristics and the edible organs, Cd accumulation varies substantially among different vegetable species (Kuboi *et al.*, 1986; Yang *et al.*, 2010). Generally, Cd accumulation in the edible parts of vegetables follows the order of legumes (Leguminosae) < melon vegetables (Cucurbitaceae) < alliums (Amaryllidaceae and Liliaceae) < root vegetables (Umbelliferae and Cruciferae) < kale vegetables (Cruciferae) < solanaceous vegetables (Solanaceae) < leafy vegetables (Cruciferae, Compositae and Chenopodiaceae) (Kuboi *et al.*, 1986; Yang *et al.*, 2010). Accumulation of Cd is not only determined by plant growth and genetic characteristics, but also depends on the concentration and bioavailability of Cd in soil. The bioavailability of Cd is influenced by soil properties including pH, soil organic matter (SOM), cation exchange capacity (CEC), soil texture, and other co-existing metals (Bolan *et al.*, 2013; Ding *et al.*, 2013; Liang *et al.*, 2013; Ye *et al.*, 2014). These factors interact and are difficult to distinguish (Ding *et al.*, 2013; Ye *et al.*, 2014). In addition, rhizosphere conditions also influence Cd bioavailability (Bolan *et al.*, 2013).

The current National Soil Environment Quality Standard (GB15618-1995) of China was formally implemented in 1996. The standard specifies 3 classes of benchmark values for heavy metals and metalloids in soil. Class I is considered to represent the natural background, Class II is set up to protect agricultural production and human health *via* the food chain, whilst Class III is for the protection of crops or forests from phytotoxicity. For Cd, the Class I value is 0.2 mg kg^{-1}, whilst the Class II values are 0.3 and 0.6 mg kg^{-1} for soils with pH $\leq$ 7.5 and pH > 7.5, respectively. The Class III value is set at 1 mg kg^{-1} for soils with pH > 6.5. The standard values for soil Cd in China are stricter than the standard or guideline values in the USA and EU countries (Zhao *et al.*, 2015).

Although the present soil environment quality standards play an important role in soil environmental protection and pollution control in China, there are debates regarding whether the different class values are appropriate (Zhao *et al.*, 2015). For example, the natural background levels of heavy metals are likely to vary according to soil parent materials and pedogenetic processes (Zhao *et al.*, 2015). Therefore, it is inappropriate to set a single Class I value for the whole country. The Class II for Cd only considers the influence of soil pH on Cd bioavailability, just with two values separated by pH 7.5. A recent study showed that soil pH in the range from 5.0 to 7.5 had a large influence on the Cd transfer coefficient from soil to rice grain (Zhu *et al.*, 2016). Other soil properties that may also influence Cd bioavailability, such as SOM and clay content (Ye *et al.*, 2012, 2014; Ding *et al.*, 2013), are not considered in the soil environment quality standards.

The objective of the present study was to determine the Cd transfer coefficient from soil to a leafy vegetable in different soil types with contrasting soil properties collected from different regions of China. Chinese cabbage (*Brassica chinensis* L.) was chosen because it is one of the most important vegetables in China and is known to be an accumulator of Cd (Kuboi *et al.*, 1986; Yang *et al.*, 2010). The threshold values of soil Cd were estimated in order to avoid exceeding Cd safety limit in leafy vegetables. The data allowed us to investigate the influences of soil properties on Cd transfer from soil to vegetable and Cd threshold values in soil.

MATERIALS AND METHODS

Soils and vegetable

In this study, 8 soils were collected from different regions of China: Yingtan of Jiangxi Province, Zhaoqing of Guangdong Province, Changsha of Hunan Province, Dujiangyan of Sichuan Province, Weifang of Shandong Province, Chongzuo of Guangxi Province, Guiyang of Guizhou Province and Baoding of Hebei Province. Soil types and physicochemical properties are shown in Table I. The vegetable used in the experiment was Chinese cabbage cv. Shanghai Green.

Pot experiment

For each type of soil, 6 exogenous Cd concentrations were set as follows: 0.00, 0.25, 0.50, 1.00, 2.00 and 4.00 mg kg^{-1}. This concentration range is considered to be environmentally realistic compared to the range of Cd concentrations reported for Chinese soils (Chinese Environmental Monitoring Station, 1990). There were 3 replicates for each concentration. A total of 144 pots were randomly arranged. Appropriate amounts of $CdCl_2$ (analytical grade) dissolved in deionized water were added to the soils and mixed thoroughly. Soil moisture content was raised to approximately 60% of