Ecotoxicology and Environmental Safety 113 (2015) 207–213

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

Major factors influencing cadmium uptake from the soil into wheat plants

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ARTICLE INFO

Article history:
Received 15 August 2014
Received in revised form
28 November 2014
Accepted 2 December 2014
Available online 12 December 2014

Keywords:
Cadmium
Wheat
Species sensitive distribution
Soil thresholds
Bioaccumulation factor

ABSTRACT

At present, soil quality standards for agriculture have not been improved for many years and are applied uniformly for a diverse variety of crops and different soil types, not fully considering the effects of soil properties on cadmium (Cd) uptake via soil–plant transfer. In this study, the characteristics of Cd transfer from soil to eight wheat varieties were investigated, and the results showed that Xiaoyan 22 was moderately sensitive to Cd. Upon growing Xiaoyan 22 in 18 different Chinese soils, we studied the major controlling factors of Cd transfer and constructed a bioaccumulation prediction model from the soil properties. The results showed that pH was the most important factor contributing to Cd uptake. After calibration for the eight wheat varieties, a continuous soil threshold model for wheat was derived for the species sensitive distribution based on food safety standards.

1. Introduction

With continuous rapid industrial development, heavy metal pollution associated with metal mining and smelting, agricultural waste, sewage sludge input, and many other processes represents a public hazard and a global problem. Cadmium (Cd) is a carcinogenic element for humans and poses risks in food safety. When exogenous Cd is present in excessive amounts in soil, crop yield and plant quality have been shown to be diminished (Bose and Bhattacharyya, 2008). For example, the Cd concentration in plant components (millet, oats, amaranth), including seeds and biomass, is increased strongly with an increase in the soil Cd concentration (Harangozo et al., 2013). It is well known that one of the most important pathways of human Cd intake is ingestion of crops grown on contaminated soils. As an example, wheat grain can become enriched with excess Cd from the environment (Wang et al., 2011).

The species sensitivity distribution (SSD) methodology is mainly used in aquatic environmental risk assessment to determine the concentration of a toxicant that is no hazard for most of species (usually 95% in Europe) in the environment (Raimondo et al., 2008). In other words, a SSD is usually constructed by fitting a cumulative distribution to a plot of species using laboratory toxicity data [e.g., median effective concentration (EC_{50}) and median lethal concentration (LC_{50})] to calculate hazardous concentration thresholds for 5% of species (HC_5) (Bossuyt et al., 2005). The SSD has no uniformly defined toxicological data requirements for the minimum number of samples, although the Organization for Economic Cooperation and Development (OECD) recommends that SSD calculation should not be carried out with data for fewer than five samples. At present, the minimum number of samples used by many authors is 8–10 (Wheeler et al., 2002). The SSD method has become an important tool for aquatic ecological risk assessment, and the U.S. Environmental Protection Agency (EPA) (Raimondo et al., 2008) has adopted many acts based on the SSD method, such as the Toxic Substance Control Act, the Clean Water Act, and the Federal Insecticide, Fungicide etc. SSD modeling has also been extended by The Netherlands to assess the impact of pollutants on the soil environment (Boekhold, 2008). At present, China's soil environmental standards greatly lag behind those for air or water, and they are confirmed based on pH, mainly from the results of actual investigations, which include primarily a short-term pot experiment conducted in the 1980s. The soil factors that affect Cd uptake by plants have been studied extensively, and those such as pH, organic carbon (OC) content, cation exchange capacity (CEC), clay content, and content of Fe and Mn oxides exhibit a remarkable influence on the transfer and availability of Cd in plants (Ding et al., 2013). The heavy metal content in wheat varies depending on the soil pH, the content of organic matter in the soil, and the proportion of clay in the soil (Tomáš et al., 2012),

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http://dx.doi.org/10.1016/j.ecoenv.2014.12.005
0147-6513/

and among these factors, soil pH is the main factor influencing the growth and rhizosphere properties of wheat (Wang et al., 2012a). Soil pH also has been shown to be a good predictor of Cd concentrations in wheat and barley (Adams et al., 2004). Building and improving soil quality standards has important implications for Cd risk assessment and protection of human health, and the key is to develop predictive models that account for the substantial influence of soil types on the availability and transfer of Cd (Rodrigues et al., 2012). A method that soil quality criteria can be derived from food quality standards published in the 1990s according to the definition of the bioaccumulation factor ($BAF = C_{plant}/C_{soil}$, where C_{plant} is adopted from the national food standard of 0.1 mg kg^{-1}) (Wu et al., 1991). The maximum allowable concentrations (MAC) of pollutant in soil have been mostly determined by the ecological environment effects method in many countries. MAC have been used in China to establish soil environmental quality standards, and also to develop eco-environmental effects (soil–plant, soil–microorganism, soil–water systems). The MAC for Cd in soil in Germany and France is based on not allowing any contamination of the food chain and in consideration of plant products. The soil Cd threshold in Japan is back-calculated from the food standard (rice), whereas the soil screening guidance of the United States EPA is derived from the human health risk assessment methods. Soil guideline values in Britain are regulated to assess the risks posed to human health from exposure to soil contamination resulting from land use. Monitored investigations are also important and essential; for example, the Cd concentration in frozen spinach from the Slovakian sales network was measured to range from 0.03 to 0.10 mg kg^{-1}, and the Cd concentration in some samples exceeded the limit of 0.04 mg kg^{-1} (Stanovič et al., 2014).

Previous and contemporary research studies have focused on the Cd soil–wheat transfer characteristics, and the relationships between BAF of wheat and major influencing soil factors have not been investigated. In addition, the soil types and sampling points reported in most studies have generally covered only narrow ranges of variation, and also, no specific HC_5 model has been constructed based on SSD curves. Therefore, it is necessary to identify the factors that influence the transfer of Cd in order to develop prediction models for wheat grown in a wide range of soil types.

In the present study, we aimed to (1) explore the transfer characteristics of Cd (exogenous salts) from a wide range of Chinese wheat-producing soils to the grain of wheat; (2) identify the major factors influencing Cd transfer and develop a BAF-based prediction model; and (3) finally, obtain a revised soil threshold (HC_5) model for wheat depending upon many thresholds in diverse normalized soil conditions through SSD curves fitted by a Log-normal function.

2. Materials and methods

2.1. Soil samples

Eighteen soil samples were collected from representative locations in 18 Chinese provinces, representing almost all regions of China and presenting a wide range of soil properties (Table 1). More serious soil pollution exists in the south compared to the north region of China, and the overall distribution of Cd concentration in the soil indicated that the Cd concentration increased from the northwest (soil 10, 13, 16) to the southeast (soil 5, 9) regions and from the northeast (soil 3, 7, 8) to the southwest (soil 2, 4) regions in general in a national survey. Samples were collected from the surface (0–20 cm), and prior to testing, the soil samples were air dried and passed through a 2-mm sieve to remove large pieces of gravel.

Soil properties were determined by routine methods (Li, 1983). Soil pH was measured by a glass electrode at a soil:water ratio of 1:2.5 (g mL^{-1}). Organic carbon (OC) content was determined based on an oil bath heating method. The CEC was assessed via a 1 mol L^{-1} NH_4Oac (AR, Xilong, China) leaching method (pH=7). The clay content was evaluated via the standard pipette method. Finally, calcium carbonate ($CaCO_3$) was determined by a gasometric method.

2.2. Pot experiment design

2.2.1. Various wheat varieties

A greenhouse experiment was carried out in Yangling District, Shaanxi Province, China. We selected soils from Shaanxi and Jiangxi Provinces (alkaline and acidic, respectively), and 8-kg samples were placed in plastic pots with a rim diameter of 35 cm and a height of 30 cm to ensure the normal growth of wheat and to preclude the possibility of nutrient deficiency. The basic fertilizer contained 0.15 g kg^{-1} N [$CO(NH_2)_2$, (AR, Xilong, China)], 0.05 g kg^{-1} P[$Ca(H_2PO_4)_2$, (AR, Xilong, China)], and 0.1 g kg^{-1} K[K_2SO_4, (AR, Xilong, China)] mixed thoroughly with an

Table 1
Basic physicochemical properties of soils from 18 sampling locations.

Soil number	Location	pH	OC (g kg^{-1})	$CaCO_3$ (g kg^{-1})	CEC (cmol kg^{-1})	Clay (%)	Background Cd (mg kg^{-1})
1	Hunan	4.90	9.00	0.00	10.85	42.91	0.19
2	Chongqing	5.74	10.14	0.00	21.34	24.96	0.20
3	Liaoning	5.74	14.99	0.00	12.19	17.32	0.17
4	Yunnan	5.92	19.87	0.00	11.10	27.52	0.30
5	Jiangxi	6.01	6.78	0.00	8.70	36.51	0.18
6	Anhui	6.25	11.62	0.00	19.08	16.84	0.11
7	Heilongjiang	6.27	20.70	0.00	28.59	19.33	0.24
8	Jilin	6.82	19.05	0.00	31.11	30.18	0.14
9	Jiangsu	6.93	27.66	0.00	26.20	45.94	0.19
10	Shaanxi	7.90	9.56	35.60	22.37	26.01	0.24
11	Hebei	7.98	4.97	17.62	8.12	10.50	0.21
12	Henan	8.07	10.32	27.50	16.01	18.18	0.23
13	Xinjiang	8.12	11.27	15.06	25.25	9.57	0.20
14	Shanxi	8.24	13.44	25.15	16.80	17.74	0.23
15	Tianjin	8.29	12.77	53.57	24.67	7.59	0.22
16	Gansu	8.37	11.18	38.51	11.23	6.66	0.21
17	Shandong	8.65	6.87	31.69	13.09	17.11	0.26
18	Inner Mongolia	8.80	9.45	11.51	11.61	10.51	0.22