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Determination and validation of soil thresholds for cadmium based on food quality standard and health risk assessment

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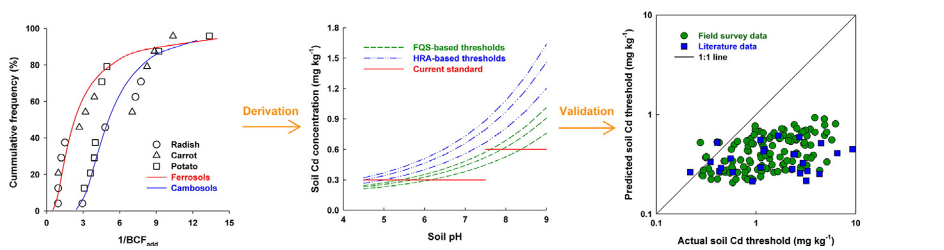
HIGHLIGHTS

- Species sensitivity distribution was applied to derive soil thresholds for Cd.
- Food quality standard as well as health risk assessment were taken into account.
- The derived soil thresholds were independently validated to be reliable.

GRAPHICAL ABSTRACT



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ABSTRACT

Cadmium (Cd) is an environmental toxicant with high rates of soil-plant transfer. It is essential to establish an accurate soil threshold for the implementation of soil management practices. This study takes root vegetable as an example to derive soil thresholds for Cd based on the food quality standard as well as health risk assessment using species sensitivity distribution (SSD). A soil type-specific bioconcentration factor (BCF, ratio of Cd concentration in plant to that in soil) generated from soil with a proper Cd concentration gradient was calculated and applied in the derivation of soil thresholds instead of a generic BCF value to minimize the uncertainty. The sensitivity variations of twelve root vegetable cultivars for accumulating soil Cd and the empirical soil-plant transfer model were investigated and developed in greenhouse experiments. After normalization, the hazardous concentrations from the fifth percentile of the distribution based on added Cd ($HC5_{add}$) were calculated from the SSD curves fitted by Burr Type III distribution. The derived soil thresholds were presented as continuous or scenario criteria depending on the combination of soil pH and organic carbon content. The soil thresholds based on food quality standard were on average 0.7-fold of those based on health risk assessment, and were further validated to be reliable using independent data from field survey and published articles. The results suggested that deriving soil thresholds for Cd using SSD method is robust and also applicable to other crops as well as other trace elements that have the potential to cause health risk issues.

1. Introduction

Cadmium (Cd), a nonessential metal for organisms, is a significant health hazard. Food accounts for about 90% of the Cd exposure in the general non-smokers due to the high soil-plant transfer rates of Cd relative to other potentially toxic metals (Clemens et al., 2013). Cd contamination of food is a consequence of widespread contamination of soil. Therefore, it is essential to establish accurate soil thresholds for the safe management of soil in agricultural producing area.

Generally, soil thresholds are calculated from the maximum levels for potentially toxic metals in food products for the various crops and the soil-plant transfer model (de Vries and McLaughlin, 2013). The

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food quality standards (FQSs) for contaminants are set according to different food categories, such as cereals, leafy vegetables, root vegetables, fruits, beans, nuts, etc. (Shao et al., 2014). However, the current soil quality standards (SQSs) of potentially toxic metals used for agriculture in many countries around the world do not consider the diverse crop species and cultivars and the effects of soil properties, and therefore may be either over- or under-conservative, resulting in unnecessary economical or ecological costs (Recatalá et al., 2010). Therefore, it is urgent to revise and improve the soil thresholds. Previous studies have derived soil thresholds inversely from the soil-plant transfer model developed either from field contaminated soils or from metal-spiked soils. However, the derivation method based solely on field sampling without considering the soil contamination level often result in the poor relationship between crop and soil metal concentrations (McBride et al., 2014). The derived soil thresholds would be unrealistically high if the soil-plant transfer model developed from field polluted soils with too high metal concentrations was used (Zhang et al., 2016). Thus, it was hypothesized that data generated from soils with proper Cd concentration gradient could improve the accuracy of derived soil thresholds. In studies conducted with the spiking of soluble metal salts and the use of pots, the accuracy of the developed prediction model when extrapolating to field conditions and the applicability of the suggested thresholds are unknown without validation on long-term contaminated field soils (Ding et al., 2013; Lu et al., 2017). Furthermore, these soil thresholds were derived from a certain crop cultivar without considering the species sensitivity variations. Therefore, the protection level of the derived soil thresholds was unknown and they are probably unapplicable to other cultivars.

Species sensitivity distributions (SSDs) are commonly used to derive threshold values for contaminants. After estimation of the SSD parameters using statistical extrapolation methods, a hazardous concentration from the fifth percentile of the distribution (HC5) is calculated. The HC5 is the concentration at which <5% of the species within an ecosystem is expected to be affected and is often used for deriving environmental quality standards (Korsman et al., 2016). Very few studies have applied the SSD methodology to derive soil thresholds due to the lack of data generated from different species and different soil types (Doolette et al., 2016).

A non-ignorable amount of potentially toxic metal in the edible parts of leaf vegetables or cereal grains could come from atmospheric deposition (Xiong et al., 2014). Therefore, the related risks of food safety and human health would be underestimated if only soil-plant transfer was taken into account. However, this is not the case for root vegetables. The accumulated potentially toxic metals in the underground edible parts of root vegetables mainly originated from the soil (De Temmerman et al., 2012), indicating that the derived soil thresholds for root vegetables would be more accurate.

Soil thresholds for Cd greatly rely on the FQS and/or the tolerable dietary intake guideline. Recently, it has been demonstrated that although FQSs are set to protect human health, their establishment is also affected by policy compromises and not always based on toxicological reference values. Hence, they should not always be used as proxies for risk assessment (Augustsson et al., 2015). However, the soil thresholds based on health risk assessment (HRA) have not been derived using SSD method before.

Therefore, taking root vegetable as an example, the present study aims to investigate the feasibility to the approach which incorporates species sensitivity and bioavailability to derive and compare the soil thresholds for Cd based on the FQS as well as HRA, and then validate the derived FQS-based soil thresholds using independent data from field survey and published articles to check their validity and applicability.

2. Procedure and methods

2.1. Framework for deriving soil thresholds for Cd

In brief, the procedures of deriving soil thresholds for Cd included, first, the investigation of the sensitivity distributions of different vegetable cultivars for accumulating Cd. The second step is the construction of the prediction model for Cd transfer from soil to vegetable. The third step is the verification of cross-species extrapolation of the prediction model and the normalization of Cd bioaccumulation data. Finally, the SSD curves were constructed and HC5 values were calculated, and then the prediction model for HC5 was developed as a function of soil properties.

2.2. Investigation of sensitivity distributions and development of prediction model

Twenty-one soils with a wide range of soil properties were collected throughout China. The soils were selected to be representative of the major soil types and the distribution of soil pH of agricultural soils in China. The detailed information of sampling location, and physico-chemical properties was given by Ding et al. (2013). Firstly, a greenhouse study was conducted to investigate the sensitivity distributions of different root vegetable cultivars for accumulating Cd using acidic Ferrosols (pH = 4.84, typical variable charge soil in central subtropical China) and neutral Cambosols (pH = 6.93, typical constant charge soil in northern temperate China). Twelve cultivars of root vegetables (each four for radish, carrot, and potato) widely cultivated in China were selected for the experiment. Then, the empirical soil–plant transfer models were developed from a carrot cultivar (New Kuroda) cultivated in the twenty-one soils in the following greenhouse study.

The uncontaminated soils were spiked with different amounts of soluble Cd salt ($3CdSO_4{\cdot}8H_2O$). Three Cd addition treatments were used: the control (no exogenous Cd added to soil), low-Cd (equal to

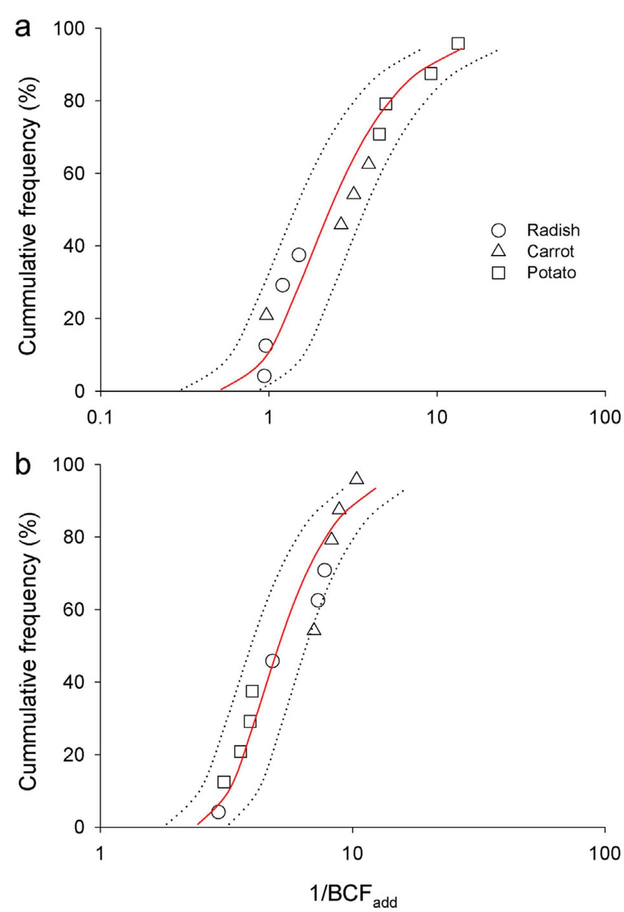

Fig. 1. Species sensitivity distributions of the twelve root vegetable cultivars grown in Ferrosols (a) and Cambosols (b) fitted by Burr Type III distribution. BCF_{add} refers to bioconcentration factor based on added soil Cd. The solid and dotted lines represent Burr Type III fitted lines, and 95% confidence intervals, respectively.