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Determination of Soil Cadmium Threshold for Potato

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In this study, pot experiments were conducted to investigate the characteristics of Cd transfer to potato tubers from two types of soil. The results showed that the Log-normal and Burr III functions can be used to determine the sensitivity of different potato varieties to Cd as well as the soil Cd threshold. With regard to the prediction accuracy, the root mean squared error (RMSE) values for the total Cd bioaccumulation factor (BAF_{total}) calculated with both functions were smaller than those for exogenous Cd bioaccumulation (BAF_{add}) in acidic and alkaline soils, indicating that BAF_{total} is more appropriate for the calculation of the soil Cd threshold. The average Cd threshold values in acidic soil calculated with the Log-normal and Burr III functions were 0.411 and 0.461 mg kg^{-1}, and the average values in alkaline soil were 0.716 and 0.888, respectively. The Log-normal function can also be applied to fit the sensitivity distributions of different species for the development of appropriate soil Cd threshold values for conservation purposes.

Keywords: cd, potato, bioaccumulation, food safety, soil threshold

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INTRODUCTION

Cadmium (Cd) is a toxic heavy metal that is harmful to plants, microorganisms and humans (Zhong, et al., 2015). The evaluation of soil Cd levels and Cd transfer from the soil to plants is therefore a critical issue. Potato is the fourth most important crop in China, behind wheat, rice and corn. The ecology of Karst areas is fragile and human activities are more likely to cause soil Cd pollution in these areas. Therefore, it is necessary to pay more attention to Cd transfer from the soil to crops in Karst areas (Zhang, et al., 2020).

The Cd content in different organs generally increases in the order of leaves > stem/root > tuber (Chen, et al., 2014). The Cd content in the tuber is less than that in other organs and most of the Cd is retained by other organs (Ye, et al., 2020). Soil properties such as pH or organic matter (OM) markedly influence the distribution of metals between the phytoavailable and non-phytoavailable sections of a plant (Pinto, et al., 2015); (Hough, et al., 2004). Other metal ions can also affect plant absorption of Cd from the soil; for instance, correlation analysis of different potato varieties showed a strong positive relation between the bioaccumulation of Cd and the presence of zinc (Zn), copper (Cu) or manganese (Mn) (Ashrafzadeh, et al., 2017). The plant species also affect soil Cd uptake. For example, the tomato genotype affects the nutritional value, fruit quality, yield, etc, and Cd-tolerant cultivars were found to accumulate more Cd than sensitive cultivars (Carvalho, et al., 2018). The results of these studies confirmed that Cd uptake by plants is influenced by various factors including the soil properties and crop varieties. Biaoaccumulation factor (BAF) is used to study the transfer of a pollutant from the soil to plants and to calculate the threshold value for the pollutant in the soil to ensure food safety. A prediction model for Pb transfer to wheat from 17 soil types with different Pb levels in China was fitted using the BAF and soil properties to determine the soil

Pb threshold (Liu, et al., 2016). Some scholars developed and compared regression models based on BAF for the uptake of Cd by potatoes through field investigations (Novotna, et al., 2015).

The cumulative probability distribution method have been used to evaluate the risk of pollutants in humans and are helpful to establish the soil threshold for heavy metals as well as for soil screening. The species sensitivity distribution (SSD) is a typical cumulative probability distribution that reflects the differences in the sensitivity of different species to the same pollutant (Liu, et al., 2015). Environmental toxicity data for pollutants such as the concentration necessary to achieve 50% of the maximal effect (EC_{50}), no observed effect concentration (NOEC) and BAF for a limited number of species obtained through biological toxicity tests are sampled based on the SSD. Establishing a threshold that covers the fifth percentile of the SSD protects the majority of the species in an ecosystem (van der Hoeven, 2001). This strategy is applied more frequently to water environments; for example, the SSD for nine compounds indicates that crustaceans are the most sensitive species to anticancer drugs in aquatic ecosystems (Li D et al., 2021). Furthermore, it has been increasingly applied to soil environments in recent years. A soil-plant transfer model was applied to Cd data for 183 soil-plant pairs to fit the SSD and 5 grades of Cd sensitivity were obtained based on the Cd-BAF (Li, et al., 2019). Many function models are available for SSD fitting, including the Burr III, Log-normal, Log-logistic and Gamma functions. The Gaussian distribution function was used to determine the cumulative probability distribution for vegetables and the soil Cd threshold in the Hunan Province of southern China as well as to implement a reasonable soil Cd risk assessment strategy for the locality (Yang et al., 2016a). The potential health risk to humans from Cd exposure was evaluated using the target hazard quotient (THQ) and the probability distribution of THQ for 324 vegetable samples in Shandong, Jiangsu, Yunnan Province in China was identified with the Log-normal function (Hu, et al., 2018). The Cd toxicity threshold for paddy soil was determined based on the variation of BAF in various rice cultivars using SSD fitted with the Burr III function (Song, et al., 2015). The appropriate model depends on the specific situation in terms of the polluted species and the regulation of the environment.

In the present study, we aimed to: 1) explore the transfer of Cd from two types of soil with different pH values to potato tubers of different cultivars; 2) compare the fit of SSD curves using the Log-normal and Burr III functions for different potato cultivars in the two soil types; and 3) obtain a soil threshold value for the safe production of potato using different calculation methods for BAF.

MATERIALS AND METHODS

Pot Experiments

Soil was collected from two Karst geological regions in China, specifically from Weining and Guiyang cities in Guizhou Province. Soil samples were collected from the surface of a field (0–20 cm) in these regions, air dried and passed through a 2 mm sieve to remove large pieces of gravel prior to the pot experiments. The base Cd concentrations were 0.61 and 0.37 mg kg^{-1} for the Weining (yellow) and Guiyang (calcareous) soil, respectively. The two soils are the main soil types in Guizhou province. Soil properties were determined using standard methods. Soil pH was determined using a glass electrode with a soil:water ratio of 1:2.5 (g ml^{-1}). The pH values for the Weining and Guiyang soil were 4.8 and 7.8. The measured OM values were 24.5 and 48.5 g kg^{-1}, respectively, using the potassium dichromate oxidation method. Ten commercial potato varieties commonly grown in the local area, namely Eeshu 5 (E5), Lishu 15 (L15), Qianyu 8 (QY8), Qingshu 9 (QS9), Weiyu 5 (W5), Lishu 13 (L13), Hongbaoshi (HBS), Heimeiren (HMR), ChuangyuA5e (CA5e) and Weiyu 7 (W7), were used in the experiments.

The potato varieties were planted in the two soil types in the way of pot experiment (greenhouse). Six kilograms of soil was placed in a plastic pot to ensure the normal growth of the potatoes. Exogenous Cd in solution ($3CdSO_4\ 8H_2O$) was added to the soil and mixed uniformly. Two treatments were applied, with three replicates for each pot. The control treatment (CK) lacked additional Cd, and 0.9 mg kg^{-1} Cd was mixed with the two soil types for the Cd treatment. The amount of Cd added was based on the risk value for Chinese Cd soil contamination in agricultural land (0.3 mg kg^{-1} for soil pH ≦ 7.5, 0.6 mg kg^{-1} for soil pH > 7.5). Additionally, 0.15 g kg^{-1}N ($CO(NH_2)_2$), 0.05 g kg^{-1} P($Ca(H_2PO_4)_2$) and 0.1 g kg^{-1} K (K_2SO_4) were added to each pot as the base fertilizer. The treated soil was left to equilibrate for 40 days to allow the behavior of Cd ions in the soil to stabilize. Potatoes with similar sizes and weights were selected for planting in the pot experiments. The potatoes were watered with deionized water to ensure that the Cd absorbed by the plants came from the soil. The soil moisture content was maintained at about 70% of the water holding capacity.

Detection of Cd in Soil and Plants

After passing the soil through a 100 mesh sieve, 0.1 g was weighed (accurate to 0.0001) and transferred to a polytetrafluoroethylene (PTFE) tank. Afterward, 3 ml nitric acid, 1 ml hydrochloric acid and 1 ml hydrofluoric acid were added and the capped tank was placed in a matched steel pipe before digesting for 20 h at 180°C on an electric heating plate. Perchloric acid (1 ml) was added as the acid driver. After digestion of the soil sample, the digestion solution was transferred to a 50 ml volumetric flask and a constant volume was maintained with ultrapure water. Finally, 10 ml of the supernatant from the digested sample solution was collected and the Cd concentration was measured using inductively coupled plasma mass spectrometry (ICP-MS; Thermo Fisher Scientific, Waltham, MA, United Sates, x2). The basic test conditions was injection speed: 0.8 ml min^{-1}; atomization gas flow rate: 0.92 ml min^{-1}; auxiliary gas flow rate: 0.7 ml min^{-1}; cooling gas: 13 L min^{-1}; the detection limit of the instrument is less than 1 ppb.

Potato tubers were collected at maturity and washed three times successively with tap water and purified water to remove soil particles from the surface. The potato tubers were placed in a

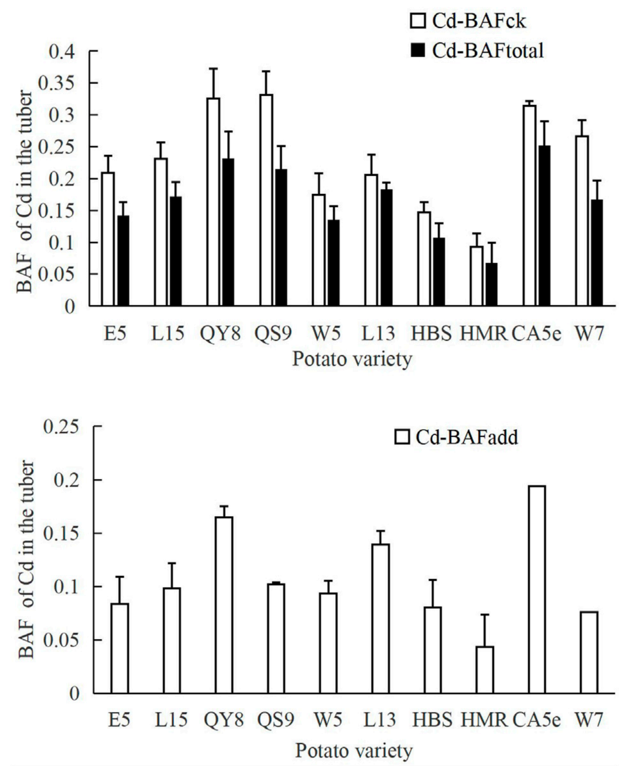

FIGURE 1 | BAF_{ck}, BAF_{total} and BAF_{add} for different potato varieties in Weining soil.

105°C electric oven for 15 min to remove green sections and then dried to a constant weight at 75°C. The plant samples were ground and stored for determination of the Cd content. We weighed 0.2 g (accurate to 0.0001) of edible plant samples into a PTFE tank, then added 5 ml nitric acid and two to three drops of hydrofluoric acid for 12 h for pre-digestion. The initial digestion solution was heated to 160 °C and digested for 8 h to remove OM. After cooling, a constant volume of 50 ml was maintained. The determination method for the Cd content in the plants was the same as that for the soil. For quality control, all the acid reagents used were of high grade purity. The glassware and PTFE tube used for digestion were soaked in 25% nitric acid solution for 12 h before use. The soil reference material GSS-5 and plant reference material GBW10021 were adopted for quality control.

Calculation Method for BAF

BAF represents the ratio of the heavy metal concentration in plants to the heavy metal concentration in the soil environment. The BAF for the CK treatment (BAF_{ck}) was calculated using the equation:

$$BAF_{ck} = C_{CK-plant} / C_{CK-soil} \tag{1}$$

Where, $C_{CK\text{-}plant}$ and $C_{CK\text{-}soil}$ are the heavy metal concentrations in the plants and soil for the CK treatment, respectively.

The BAF for total Cd (BAF_{total}) was calculated with the equation:

$$BAF_{total} = C_{plant} / C_{soil} \tag{2}$$

Where, C_{plant} is the concentration of heavy metals in the plants and C_{soil} is the concentration of heavy metals in the soil for the Cd treatments.

Some scholars (Ding, et al., 2013) proposed a BAF calculation method for exogenous pollutants that only considers the effects of exogenous pollutants on plants. The BAF for exogenous Cd (BAF_{add}) was calculated with the equation:

$$BAF_{add} = \left(C_{plant} - C_{CK-plant}\right) / \left(C_{soil} - C_{CK-soil}\right) \tag{3}$$

Where, C_{plant} and C_{soil} are the concentrations of heavy metals in the plants and soil for the Cd treatments, respectively.

RESULTS AND DISCUSSION

BAF for Cd in Two Soil Types

The variability of BAF is important for the assessment of Cd exposure for plants in contaminated soil and represents the current contamination situation (Augustsson, et al., 2015). As seen in **Figure 1**, the total Cd-BAF for tubers grown in Weining soil varied between 0.09 (HMR) - 0.33 (QS9) for BAF_{ck} and 0.07 (HMR) - 0.25 (CA5e) for BAF_{total}. The average BAF_{ck} and BAF_{total} values for the 10 potato varieties evaluated in this study were 0.23 and 0.17, respectively. Twenty-one potato samples were collected from a field in the Czech Republic and the average BAF was 0.34, which was greater than the values obtained in the current study because of differences in the soil properties (Novotna, et al., 2015). The BAF_{ck} for each potato variety was slightly higher than the corresponding BAF values for the Cd treatments. In contrast, the BAF_{ck} for carrot in 21 soil types from China was less than the BAF_{total} for the Cd treatment (soil spiked with 0.6 mg kg^{-1} Cd) (Ding, et al., 2013). The difference in the results may be attributed to the use of different crops and the crop growth conditions. For both the CK and Cd treatments, the HMR potato variety accumulated the least Cd while the CA5e variety accumulated the most. In a previous study, three potato cultivars that easily uptake Cd from the soil, known as Cd accumulators, were identified from 10 cultivars based on the BAF and plant Cd concentration (Ashrafzadeh, et al., 2017). These studies demonstrate that identifying crop genotypes with low or high Cd accumulation based on the enrichment factor is an effective method to avoid Cd pollution in food.

The BAF_{add} of Cd for the 10 potato varieties evaluated in this study ranged from 0.04 (HMR) to 0.19 (CA5e), and the average BAF_{add} was 0.13, which was slightly less than the average BAF_{total} and BAF_{ck}. The BAF_{total} and BAF_{ck} indicated that the CA5e potato variety could easily uptake soil Cd, while the HMR and HBS varieties absorbed less Cd from the soil. A prediction model was established based on soil Cd content, plant Cd content and soil properties (pH and organic carbon) and the results showed that the BAF_{total} and BAF_{add} can be used to develop a prediction

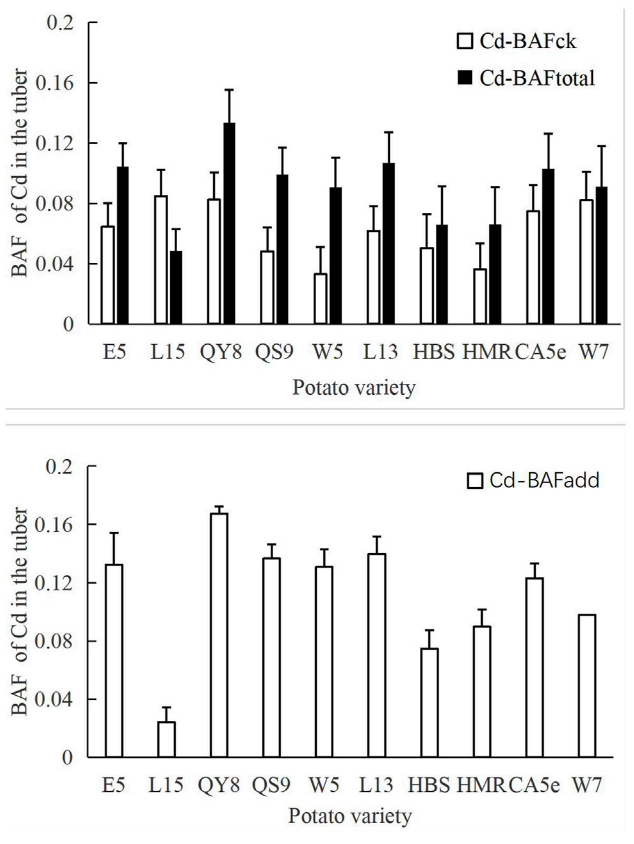

FIGURE 2 | BAF_{ck}, BAF_{total} and BAF_{add} for different potato varieties in Guiyang soil.

TABLE 1 | RMSE of soil Cd threshold calculated with two functions.

Soil	Treatment	Function	
		Log-normal	Burr III
Weining	BAF_{ck}	0.0036	0.0029
	BAF_{total}	0.0075	0.0060
	BAF_{add}	0.0157	0.0162
Guiyang	BAF_{ck}	0.0219	0.0283
	BAF_{total}	0.0104	0.0066
	BAF_{add}	0.2321	0.4679

Soil Cd threshold in two soil types.

TABLE 2 | Soil Cd threshold calculated with two functions for two soil types.

Soil	Treatment	Function	
		Log-normal	Burr III
Weining	BAF_{ck}	0.231	0.284
	BAF_{total}	0.322	0.394
	BAF_{add}	0.486 + C_b	0.511 + C_b
	average	0.411	0.461
Guiyang	BAF_{ck}	0.937	1.108
	BAF_{total}	0.680	0.783
	BAF_{add}	0.337 + C_b	0.580 + C_b
	average	0.716	0.888

BAF_{add}, only considers the effect of exogenous Cd addition. The field base value of Cd was added to the soil threshold, and C_b was 0.194 mg/kg.

model for Cd transfer from the soil to vegetables as well as for identifying soil thresholds for food safety (Liang, et al., 2013). Empirical soil-carrot transfer models were developed for 21 soil types in China and the prediction model for added Cd was found to be better than the model for total Cd (R^2: 0.77 > 0.73) (Ding, et al., 2013). These results indicated that BAF_{total} and BAF_{add} are both valuable parameters for studying soil Cd uptake in crops and calculating the soil threshold.

The Cd-BAF of tuber grown in Guiyang soil ranged from 0.03 (W5) to 0.08 (L15) for BAF_{ck} and from 0.05 (L15) to 0.13 (QY8) for BAF_{total}. The average BAF_{ck} and BAF_{total} of the tubers were 0.06 and 0.09 for different potato varieties, respectively. Some researchers studied the accumulation of Cd in potato with different soil Cd levels (soil Cd < 25 mg kg^{-1}) and found that the BAF_{total} of the tubers ranged from 0.20 to 0.81. The BAF_{total} values in these studies were larger than our results, probably due to higher Cd pollution (<25 mg kg^{-1}) and low OM content (14.6 g kg^{-1}) in the soil compared to our soil conditions (soil Cd: 0.9 mg kg^{-1}, OM: 48 g kg^{-1}) (Chen, et al., 2014). Most of the BAF_{total} values were higher than the BAF_{ck} values for specific varieties in the alkaline Guiyang soil and the opposite results were obtained in the acidic Weining soil. The biggest difference between the BAF_{ck} and BAF_{total} was found in the W5 variety, which had a BAF_{total} value that was 2.74 times greater than the BAF_{ck}. The BAF_{add} ranged from 0.02 (L15) to 0.17 (QY8), with an average BAF_{add} of 0.11, which was close to the BAF_{total} for the Cd treatments.

The transfer of Cd from the soil to the potato tubers was limited with the HMR and HBS varieties in both the Weining soil and Guiyang soil for the CK and Cd treatments. The QY8 and CA5e varieties were sensitive to Cd uptake from the Guiyang soil, while QY8, QS9 and CA5e were sensitive to Cd uptake from the Weining soil. QY8 and CA5e were sensitive to Cd uptake with the CK and Cd treatments in the Weining and Guiyang soils, as indicated by the high BAF_{total} and BAF_{add}. The BAF_{add} and BAF_{total} values demonstrated that Cd-sensitive and insensitive potato varieties were similar in the two soil types with different pH values and the genotype affected food safety in the polluted soils.

The BAF_{ck} and BAF_{total} values in the alkaline Guiyang soil differed from those in the acidic Weining soil. **Figures 1**, **2** show that the ability of the potato varieties to absorb Cd in acidic soil was stronger than that in alkaline soil for both the CK and Cd treatments based on the average BAF_{total} and BAF_{ck}. pH is an important factor that affects the adsorption, desorption, precipitation, dissolution and complexation of heavy metals in the soil and can directly or indirectly affect the retention of heavy metals in the soil. In a previous study in which the soil pH was increased by 0.50 units through lime addition, the uptake of Cd by rice grain decreased by 35.3% and the Cd transfer ratio increased as the soil pH decreased in acidic and alkaline soils (Zhu, et al., 2016). The results of the current study demonstrated that the soil type and genotype significantly affect Cd uptake by potato and so

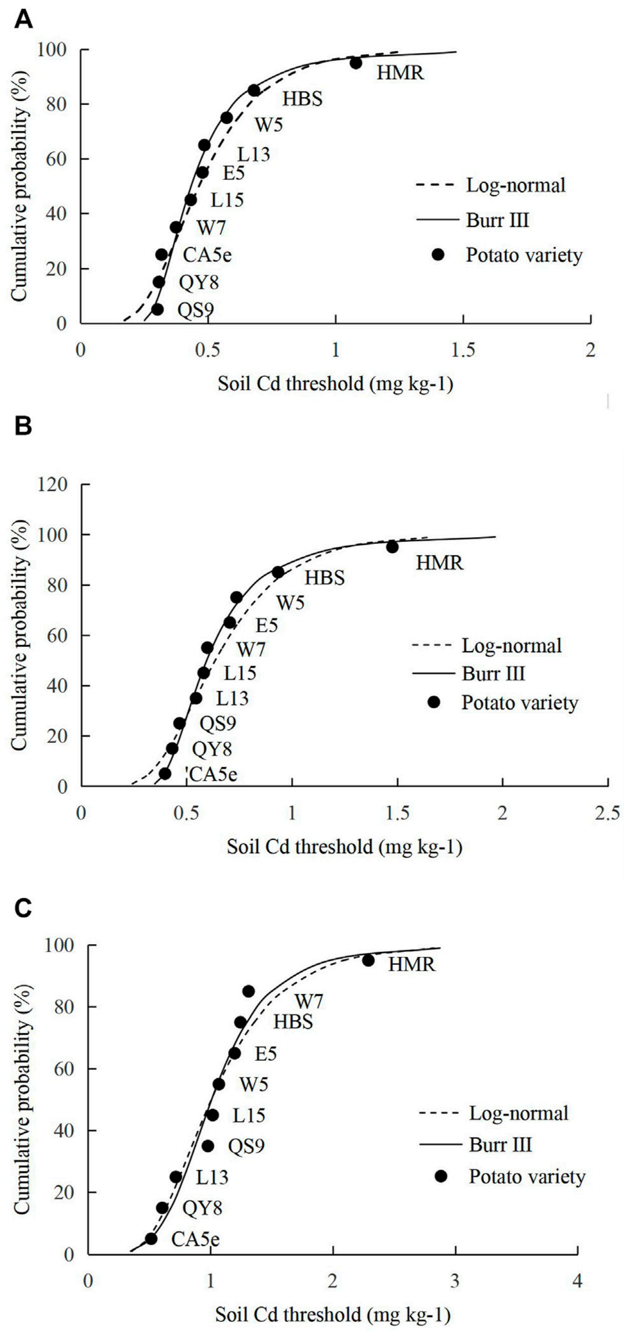

FIGURE 3 | SSD curves of different potato varieties in Weining soil. **(A)**. BAF_{ck}, **(B)**. BAF_{total}, **(C)**. BAF_{add}.

does the interaction between these two factors. Luyin No. One was identified from four potato cultivars as a suitable cultivar for planting in slightly Cd-contaminated soils (<0.6 mg kg^{-1}). The average reported BAF_{add} for different cultivars is 2.3, which is less than the reported BAF_{total} value (2.76) in soil with pH 6.9 and is similar to the results for our acidic Weining soil (BAF_{add} 0.13 < BAF_{total} 0.17) (Ding, et al., 2014). In general, there was significant difference between the Weining soil and Guiyang soil in both the BAF_{ck} and BAF_{total}, however, BAF_{add} was different from BAF_{ck} and BAF_{total} (**Table 1** in the **Supplementary Data S1**). The BAF_{ck}, BAF_{total} and BAF_{add} of some varieties have significant differences, while other varieties have no significant differences among each other in the two soils, moreover, the significant difference of the BAF_{total} was similar to that of BAF_{add} (**Table 2** in the **Supplementary Data S1**).

Comparison of Log-Normal and Burr III Functions

SSD is used to create a cumulative probability distribution curve with toxicity data that follow certain probability distributions such as the Log-normal distribution. A cumulative probability of "p" indicates that (100-p)% of organisms in the ecosystem are relatively safe in an environment containing the pollutant at the given concentration (Maltby, et al., 2009). It is worth noting that the "p" value is determined by the local environment safety management department rather than science, and 5% is often used as the threshold value for ecological safety. The soil Cd threshold for each potato variety was obtained based on the BAF ($C_{soil\ threshold}$ = 0.1/BAF, 0.1 mg kg^{-1} is the limit for the Chinese food safety standard (GB 2762–2017); BAF can refer to BAF_{ck}, BAF_{total} or BAF_{add}). The $C_{soil\ threshold}$ of 10 potato varieties was applied to calculated the final soil Cd threshold in order to protect 95% potato and the value of soil Cd threshold was equaled to the 5% cumulative probability. The Burr III or Log-normal function was used to generate an SSD curve and a 5% cumulative probability to protect 95% of species was set as the final soil threshold to protect most potato varieties from Cd damage. A similar method was applied to determine the Cd soil threshold for wheat in different soils using the SSD fitted with the Log-normal function (Liu, et al., 2015). The soil Cd threshold increased with the increase of the cumulative probability. When the cumulative probability was less than 30%, the soil threshold calculated with the Log-normal function was less than that calculated with the Burr III function. In contrast, when the cumulative probability was greater than 30%, the opposite results were obtained for the soil threshold calculated with the two functions. The BAF_{ck} indicated that the sensitivity levels of the QS9 and HMR varieties to soil Cd were significantly different. QY8 and QS9 easily absorbed Cd from the soil and other potato varieties were relatively insensitive to Cd compared to these two varieties (**Figure 3A**). The BAF_{total} values for the potato varieties were evenly distributed on the two SSD curves. The soil Cd threshold fitted with the Log-normal function was less than that obtained with the Burr III function at a low cumulative probability (<30%) and was similar to the BAF_{ck}. The HMR variety was the most insensitive to Cd, evidenced by both the BAF_{ck} and BAF_{total}. The soil Cd threshold was obtained based on the BAF_{total} and the SSD curves fitted with the Burr III and Log-normal functions were "S-shaped" (**Figure 3B**). When we focused on the effect of Cd addition on the bioavailability of potato tubers (BAF_{add}), we found that the CA5e potato variety was relatively sensitive to soil Cd while the HMR variety had a strong resistance to soil Cd uptake. The curves calculated with the Burr III and Log-normal functions were almost the same when the cumulative probability

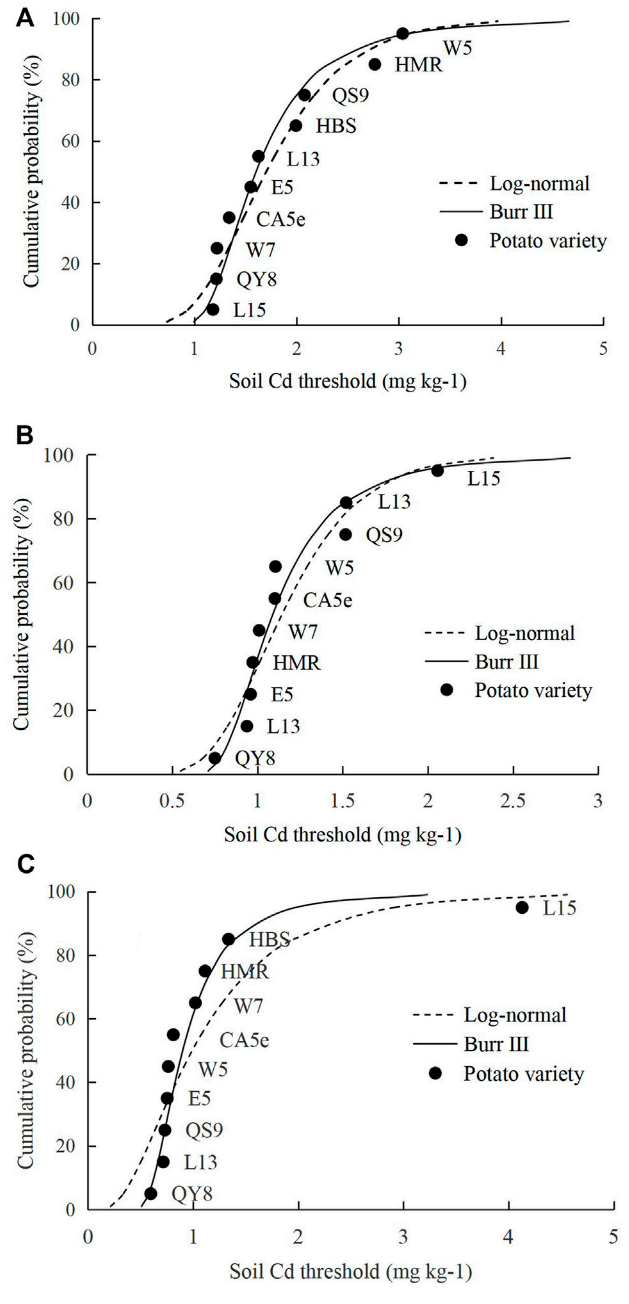

FIGURE 4 | SSD curves of different potato varieties in Guiyang soil. **(A)**. BAF_{ck}, **(B)**. BAF_{total}, **(C)**. BAF_{add}.

was less than 5%; therefore, the soil Cd thresholds calculated with the two functions were relatively similar when the protection of more than 95% of potato varieties was taken into consideration (**Figure 3C**). Based on a combination of the BAF_{total} and BAF_{add} values, the CA5e and HMR potato varieties were the most sensitive and insensitive to soil Cd in Weining soil in Karst areas, respectively. The identification of Cd-resistant potato varieties is helpful for local food safety. In a study using SSD, Xiangzao 17 was identified as the most sensitive rice cultivar to soil Cd among 20 rice cultivars based on the cumulative probability distribution curve calculated with 1/BAF. The results demonstrated that the SSD method was helpful to screen sensitive and insensitive varieties for pollutants (Song, et al., 2015).

The soil threshold for Cd established with the Burr III function was higher than that calculated with the Log-normal function at a low cumulative probability, and the opposite was true for a high cumulative probability (**Figures 4A,B**). This result was similar to the results for the SSD curves of BAF_{ck} and BAF_{total} for the Cd treatments in Weining soil. However, the SSD curve fitting for BAF_{add} with the Burr III function was quite different from that with the Log-normal function, and unlike the SSD curve in acidic Weining soil (**Figure 4C**). QY8 was sensitive and L15 was insensitive to Cd uptake, as indicated by their respective curves for BAF_{total} and BAF_{add}. The Burr III function is considered the best function for soil Cd threshold calculations and has been used to determine the soil Cd threshold for vegetables including potato in acidic and neutral soils based on the BAF_{add}. Cd-sensitive species and hazardous concentrations within the fifth percentile, reflecting the protection of 95% of species, can also be determined using the SSD (Ding, et al., 2018). The sensitivity levels of the potato varieties were similar in the acidic Weining soil and the alkaline Guiyang soil, as indicated by the BAF_{total} and BAF_{add}, but differed from the sensitivity levels with CK treatment, as indicated by BAF_{ck}. The toxicity sensitivity of different potato varieties to the soil Cd can be directly observed from the SSD curves based on the BAF_{ck}, BAF_{total} and BAF_{add}, which reflect the transfer capacity of heavy metals.

The RMSE represents the deviation between the prediction and the measured value, and a smaller RMSE indicates better prediction accuracy. The RMSE between the predicted and measured soil Cd threshold values for the 10 potato varieties established with BAF_{add} was larger than that established with BAF_{ck} and BAF_{total} in the two soil types using the two functions (**Table 1**). This suggested that BAF_{total} and BAF_{ck} were more suitable for studying the transfer of Cd from the soil to plants. The predictive accuracy of the BAF_{ck} and BAF_{total} values was better in Weining and Guiyang soils, respectively. The RMSE values for the Burr III function with the BAF_{ck} and BAF_{total} values were less than those for the Log-normal function in acidic Weining soil, indicating that the Burr III function was better suited for determining the soil Cd threshold for this soil type. Log-normal was more appropriate for BAF_{add} and BAF_{ck} in alkaline Guiyang soil. The high prediction accuracy of the soil threshold for BAF_{ck}, BAF_{total} and BAF_{add} confirmed that the Burr III and Log-normal functions can both be applied to obtain the soil Cd threshold. However, the optimal function needs to be selected depending on the soil type and BAF calculation method. BAF_{add} was reported to be better for the determination of the soil Cd threshold for the safe production of rice in paddy soils (pH: 4.94–6.72) and the Burr III function is commonly used to fit SSD curves (Li L et al., 2021). The results of these studies are different from ours, in which BAF_{total} was better than BAF_{add}, probably due to different experimental conditions and species.

As shown in **Table 2**, the soil Cd threshold for the Weining soil calculated with the Log-normal function was a little less than that calculated with the Burr III function using the BAF_{ck}, BAF_{total} and BAF_{add} values. The soil Cd threshold obtained with BAF_{add} was higher than those obtained with BAF_{ck} and BAF_{total}. The average soil Cd threshold was slightly higher than the Chinese national soil standard for Cd (0.3 mg kg^{-1}). Similarly, the soil Cd threshold in Guiyang soil calculated with the Burr III function was higher than that calculated with the Log-normal function and was slightly higher than the Chinese soil screening value for agriculture (0.6 mg kg^{-1}). The soil Cd threshold for BAF_{add} was lower than those for BAF_{ck} and BAF_{total}. These findings differed from the results obtained for Weining soil. Some researchers have applied similar methods to determine the soil threshold for other pollutants. The soil Pb threshold was obtained for 12 root vegetable cultivars based on the SSD and the threshold values based on BAF_{add} were lower than the standard for Pb in the soil (Ding, et al., 2016). Risk evaluation of Cd in soil-rice systems ($n = 124$) was conducted using SSD curves from rice Cd-BAF_{total} in Hunan Province, China (Yang et al., 2016b). The soil Cd threshold obtained in this study is conducive to the protection of local potatoes from Cd pollution, the evaluation of Cd pollution and the development of soil quality guidelines.

CONCLUSION

The BAF values for different potato varieties in acidic soil were higher than those in alkaline soil for the CK and Cd treatments. The HMR and CA5e potato varieties were quite insensitive and sensitive in acidic soil, whereas QY8 and L15 were sensitive and insensitive in alkaline soil.

The soil Cd threshold values obtained with the Log-normal function using BAF_{ck}, BAF_{total} and BAF_{add} were less than those obtained with the Burr III function in the Weining and Guiyang soils. The soil Cd threshold values were in the order BAF_{add} > BAF_{total} > BAF_{ck} in Weining soil for the Log-normal and Burr III functions. The soil Cd threshold values were in the order BAF_{ck} > BAF_{total} > BAF_{add} for the Guiyang soil. The RMSE for BAF_{total} was less than that for BAF_{add} based on the two functions in the Weining and Guiyang soils, indicating that BAF_{total} was more appropriate for calculating the soil threshold of Cd compared to BAF_{add}.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material,** further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

WL: Writing—original draft preparation, Investigation and formal analysis. XH: Investigation, Writing and Editing. JZ: Experimental formal analysis and software analysis. KL: Methodology, Writing—review and editing, Formal analysis.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.808362/full#supplementary-material

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