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Distribution characteristics of cadmium and lead in particle size fractions of farmland soils in a lead–zinc mine area in Southwest China

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Abstract

Background: Cd and Pb were the main pollution elements in Pb–Zn mining areas. Several studies have focused on heavy metal pollution and risk assessment in the Huize Pb–Zn mining area. In the present study, the soil aggregate composition, chemical properties, contents and chemical fractions of Cd and Pb were analysed in soils at depths of 0–60 cm in the Huize Pb–Zn mining area. Agricultural soils were sampled at depths of 0–20, 20–40 and 40–60 cm surrounding the Pb–Zn mine. The particle size fractions were determined by the aggregate composition of macro-aggregates (0.25–2 mm), micro-aggregates (0.053–0.25 mm), silt (0.002–0.053 mm) and colloid (< 0.002 mm).

Results: There was a large proportion of the macro-aggregate (52.4%) and less of the colloid (1.8%). With a decrease in particle size, the pH, organic matter contents, cation exchange capacity, and free iron oxide increased in the soil aggregates. Although the total and available Cd and Pb contents were highest in the colloid, the macro-aggregate maximally contributed to the total Cd (48.18%), total Pb (53.48%) and available Pb (47.42%) content, and the colloid maximally contributed to the available Cd (47.21%) in soils. The Cd and Pb existed primarily as residual fractions, followed by Fe–Mn oxide fraction and the exchangeable fraction in soil aggregates. There were higher distribution factors for the residual and exchangeable fractions of both Cd and Pb in the colloid (DF > 33). Furthermore, there were close correlations between the Cd and Pb fractions and the pH and the phosphorus content and between the exchangeable Pb content and the content of organic matter, cation exchange capacity, and free iron oxide in soil aggregates.

Conclusion: Cd and Pb existed mainly in the micro-aggregate and colloid and that their chemical fractions were closely related to the chemical properties in soil aggregates of the polluted farmland.

Keywords: Lead–zinc mine, Heavy metals, Chemical fractions, Soil aggregate, Soil property

Background

China, as one of the important metal mining areas in the world, has reserved and explored lead–zinc (Pb–Zn) mines on a large scale (Wu et al. 2004). During the metal production process, the buried heavy metals that are exposed to the surface soil migrate to the surrounding environment and cause serious pollution problems in the mining area (Castillo et al. 2013; Wali et al. 2013). High contents of Cd and Pb exist in the polluted farmland soils and can be absorbed by crops and the human body via the food chain; thus, they are a threat to human health (Aigberua et al. 2017). Therefore, soils being polluted by Cd and Pb in Pb–Zn mining areas has been a significant problem.

Particle size classification has been widely used to judge the distribution of elements in soils (Shein 2009). Soil aggregates are the basic material matter and functional units in soil (Mikha and Rice 2004). The Cd and

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Pb contents in soil aggregates frequently increase with a decreasing particle size. Silt always has a maximum content of Cd and Pb due to its small size (Aydınoğlu et al. 2014; Martin et al. 2014). For instance, Pb was concentrated in silt obtained from five European cities (Ajmone-Marsan et al. 2008). In addition, a higher enrichment factor of Cd and Pb in silt was observed in both the agricultural soil of Fuyang Country in China and the mining soil in Cerdeirinha and Penedono (Zhang et al. 2013; Gomes et al. 2016).

Furthermore, the chemical fractions of Cd and Pb in particle size aggregates are related to the soil properties, such as the pH, organic matter, free iron oxide, cation exchange capacity (CEC) and phosphorus (Hu et al. 2012; Youngnam et al. 2010). The fraction of exchangeable Cd increased with a decrease in soil pH (Waterlot et al. 2011). Due to a large specific surface area and a number of functional groups, organic matter can precipitate and complex with free Cd and Pb in soils, thus increasing the fraction bound to organic matter and decreasing the effective fractions (Olaniran et al. 2013). The adsorption capacity of iron oxide for heavy metals depends on the forms of iron oxide. Because of the special morphology and micro crystal amorphous structure, aqueous iron oxide has a larger adsorption capacity for heavy metals (Tack et al. 2006; Thirumavalavan et al. 2013; Liang et al. 2017). The phosphorus content can influence the soil pH and content of phosphate ions and decrease the availability of heavy metals (Khan and Jones 2009). There were many researches on the heavy metal content and distribution characteristics of soil aggregates in urban soil, dust and arable soil (Gong et al. 2014; Soylak 2015; Jayarathne et al. 2017). However, there is less research on soil aggregates that are characteristic of Pb–Zn mining areas. The distribution characteristics and influence factors of Cd and Pb in Pb–Zn mining soils thus need further research.

Yunnan Province, located along China's south western border, is called the "Kingdom of the nonferrous metals". The Pb–Zn mine in Huize County, Yunnan Province, is an important mineral resource in China, and it has been exploited for 300 years (Li et al. 2012). Several studies have focused on heavy metal pollution and risk assessment in the Huize Pb–Zn mining area (Zou et al. 2014; Qi et al. 2016). Smelting activities were the main contributors to the high concentrations of Cd and Pb in the topsoil. The mobility of Cd in soils was higher than that of Pb. Pb contributed to the highest hazard quotient (57.0–73.9%) in the hazard index (Li et al. 2015c; Qi et al. 2016). However, the relationship between the soil aggregate composition and the characteristics of Cd and Pb has received less attention.

In the present study, the soil aggregate composition, chemical properties, contents and chemical fractions of Cd and Pb were analysed in soils at depths between 0 and 60 cm in the Huize Pb–Zn mining area. The main objectives were (1) to determine the distribution characteristics of soil aggregates and their chemical properties, (2) to analyse the vertical distribution of the Cd and Pb in soils and their chemical fractions in different particle sizes of soil aggregates, and (3) to determine the relationships between the chemical properties and the chemical fractions of Cd and Pb in soil aggregates.

Methods

Study area and soil sampling

The experimental area (26°30′–26°38′ N, 103°34′–103°42′ E) was located in Huize County, Yunnan Province, southwest China (Fig. 1). The average altitude was 2183 m and the relative elevation was 389 m. Hujiapo is smelted in the Huize Pb–Zn mining area. We sampled 12 soils in the northeast and southwest directions, and three km for each other. There were 108 samples collected and each sample was taken from the 0–20, 20–40 and 40–60 cm soil layers and repeated for three times. Those soils were air-dried and passed through a 2-mm sieve to remove rocks and roots (Yang et al. 2014).

Soil aggregate composition

To separate the air-dried soil samples, we weighed 80.0 g of each soil in 400 mL of distilled water and soaked it for 1 h. The macro-aggregate (0.25–2 mm) was separated by the wet sieve method with a 2-mm sieve and a 0.25-mm sieve. We used Stokes Law to calculate the sedimentation times and separated the residual soil suspension by the siphon method to get the micro-aggregates (0.053–0.25 mm). We used the centrifuge method to separate the silt (0.002–0.053 mm) and colloid (< 0.002 mm) (Wu et al. 2004; Frankenstein and Garcíagaines 2015). After separation, all of the soil aggregates were dried and weighted.

Analysis of soil chemical properties

Basic soil chemical properties, such as pH, organic matter, Cationic Exchange capacity (CEC), free iron oxide and phosphorus, were determined according to Lu (1999). Soil pH was measured by a Seven Easy desktop acid meter (S20K), and the water-soil ratio was 2.5:1. The organic matter content was measured by the potassium dichromate volumetric method, and we chose phenanthroline as the indicator with 0.2 mol/L $FeSO_4$ titration. The CEC content was determined by the NH_4OAC exchange method, and we used a neutral ammonium acetate solution to process soil repeatedly to acquire ammonium-saturated soil. The free iron oxide content was determined by the sodium dithionite-sodium

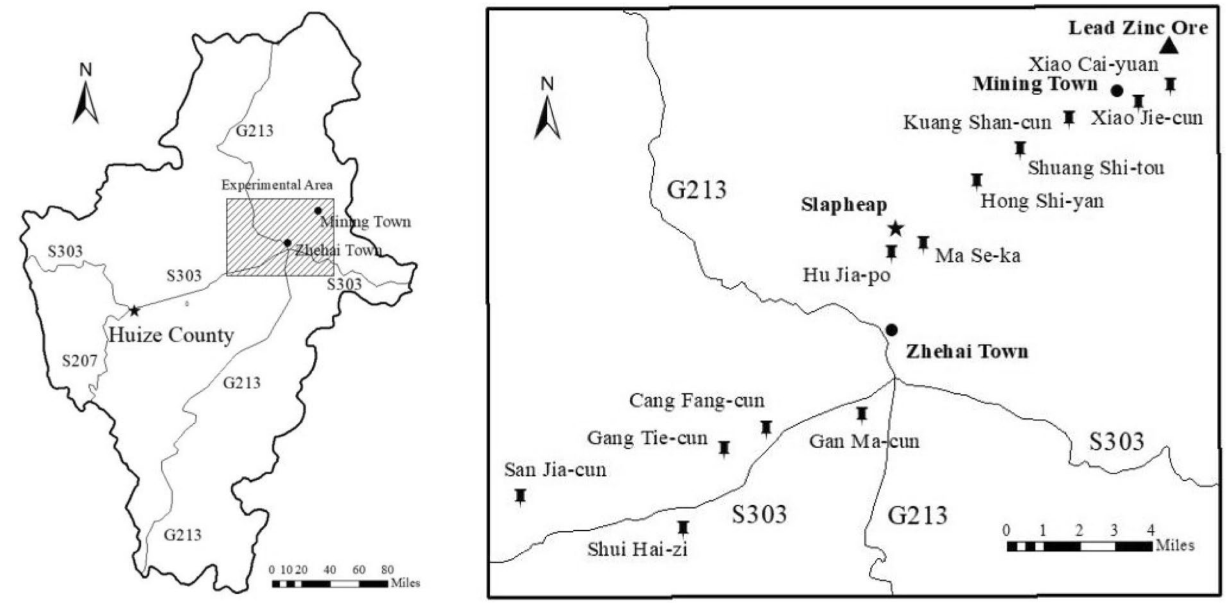

Fig. 1 Soil sampling points in the experimental area

citrate-sodium carbonate oxygen method (DCB), and the extracting solution was measured by the *O*-Phenanthroline spectrophotometric method. The phosphorus content was determined by Mo-Sb colorimetric method at a 700 mm wavelength for colorimetric determination.

Analysis of Cd and Pb elements

The total Cd and Pb in soil and different particle size fractions were measured using a strong acid (Aquaregia-$HClO_4$) pseudo-total digestion method. The available Cd and Pb were measured by DTPA extraction (Dai et al. 2004). The fractions of Cd and Pb in soil were measured by Tessier's five steps for continuous extraction: (1) exchangeable fractions; (2) carbonate-bound fractions; (3) Fe–Mn oxide-bound fractions; (4) organic matter-bound fractions; and (5) residual fraction (Tessier et al. 1979). The contents of Cd and Pb elements were determined by flame atomic absorption spectrophotometry (TAS-990).

Evaluation methodology

Distribution factor

The distribution of heavy metal factors can be used to evaluate the enrichment of heavy metals of different particle sizes in soil aggregate (DF); if $DF > 1$, the enrichment of heavy metals is in a corresponding particle size of aggregate. The index was calculated by (Acosta et al. 2009)

$$\mathrm{DF} = \mathrm{C_f}/\mathrm{C_b}$$

where C_b and C_f are the contents of heavy metals in soil and different particle sizes of aggregate, respectively.

Metal loading

The other most important pollution index to evaluate the quality of heavy metals of each particle group (GSF) is metal loading. The index was calculated by (Sutherland 2003)

$$\mathrm{GSF_{loading}} = (\mathrm{C_i} \times \mathrm{GS_i})/\left(\sum_{i=1}^{4} (\mathrm{C_i} \times \mathrm{GS_i})\right) \times 100,$$

where C_i is means the heavy metal contents in different particle sizes of soil aggregates. GS_i is means the metal percentage, and its range is between 1 and 100%.

Quality control

To assess the accuracy of the results obtained by the methods used in this study, blank solutions were also prepared in the same manner as that employed for the soil samples. No contamination with trace metals were found in the blank soil solutions that were checked. The recoveries for Fe, Cd and Pb were 99.8, 98.3 and 103.2%, respectively.

Statistical analysis

We used map software (Arc GIS 10.2) to get a map of the soil sampling points in the research area. The statistics box figure and line chart were analysed by Origin 9.0. The correlation analysis among the experiment index used the statistical software SPSS19.0, and the least significant difference was at the 0.05 probability level.

Results

Soil chemical properties at different depths

For the soils at 0–60 cm depths, the farmland soil around Lead–Zinc mine area was weak acid soil. The contents of organic matter, CEC, free iron oxide, phosphorus, Cd and Pb were higher in the 0–20 cm soil layer, but they were not obviously different among the three depths. The average contents of organic matter, CEC, free iron oxide, and phosphorus were 28.9 g/kg, 10.3 *c* mol/kg, 62.5 mg/kg and 1.8 g/kg in the 0–20 cm soil, respectively. The contents of Total Cd and Pb were 2.7 and 366.1 mg/kg in the 0–20 cm soil, respectively (Table 1).

Table 1 Chemical properties of soil and contents of Cd and Pb at 0–20, 20–40 and 40–60 cm depths

Chemical property	Soil depth		
	0–20 cm	20–40 cm	40–60 cm
pH	6.3 ± 0.9	6.6 ± 0.9	6.6 ± 0.9
Organic matter (g/kg)	28.9 ± 9.5	18.3 ± 7.3	15.3 ± 10.2
CEC (*c* mol/kg)	10.3 ± 3.3	9.9 ± 2.5	10.2 ± 3.5
Free iron oxide (mg/kg)	62.5 ± 25.2	53.6 ± 14.0	55.5 ± 16.3
Phosphorus (g/kg)	1.8 ± 0.5	1.6 ± 0.5	1.7 ± 0.5
Total Cd (mg/kg)	2.7 ± 1.1	2.3 ± 1.7	2.0 ± 1.1
Available Cd (mg/kg)	0.9 ± 0.6	0.7 ± 0.8	0.5 ± 0.2
Total Pb (mg/kg)	366.1 ± 388.5	401.1 ± 695.3	366.2 ± 523.0
Available Pb (mg/kg)	90.6 ± 78.6	85.3 ± 72.6	55.2 ± 61.2

Composition and chemical property of soil aggregates

The macro- and micro-aggregates were the priority in soil aggregate composition at the 0–60 cm depth. The largest proportion of the macro-aggregate was 69.2%. The proportion of colloid with the minimum average proportion was 1.8% (Fig. 2). Furthermore, the soil aggregates composition did not change with the soil depth.

For the chemical properties of the soil aggregates, pH increased from 6.5 to 7.9, with a decrease in particle size. Similarly, the contents of organic matter, CEC and free iron oxide increased with the decreasing particle size. Their contents were highest in the soil colloid. However, the phosphorus content was higher in the macro-aggregates and soil colloid (Table 2).

Contents of Cd and Pb in soil aggregates

The contents of total and available Cd and Pb increased with the decrease in soil particle size. The highest contents of both Cd and Pb were in the colloid and were higher than those in the other soil aggregates (Table 3). Therefore, the distribution factors of both Cd and Pb were highest in the colloid. The distribution factors of total Cd and available Cd were 39.8 and 80.5, and those of total Pb and available Pb were 16.5 and 6.5, respectively (Fig. 3).

Mass loading of cadmium and lead in soil aggregates

The macro-aggregate had the highest contribution of the total Cd, at 50.2%, followed by the colloid, at 23.6%. Conversely, the colloid had the highest contribution of the available Cd, at 46.3%, followed by the macro-aggregate, at 26.6%. For the total and available Pb, the macro-aggregate had the highest contribution sat 54.9 and 46.5%, respectively. Following was the micro-aggregate (Fig. 4).

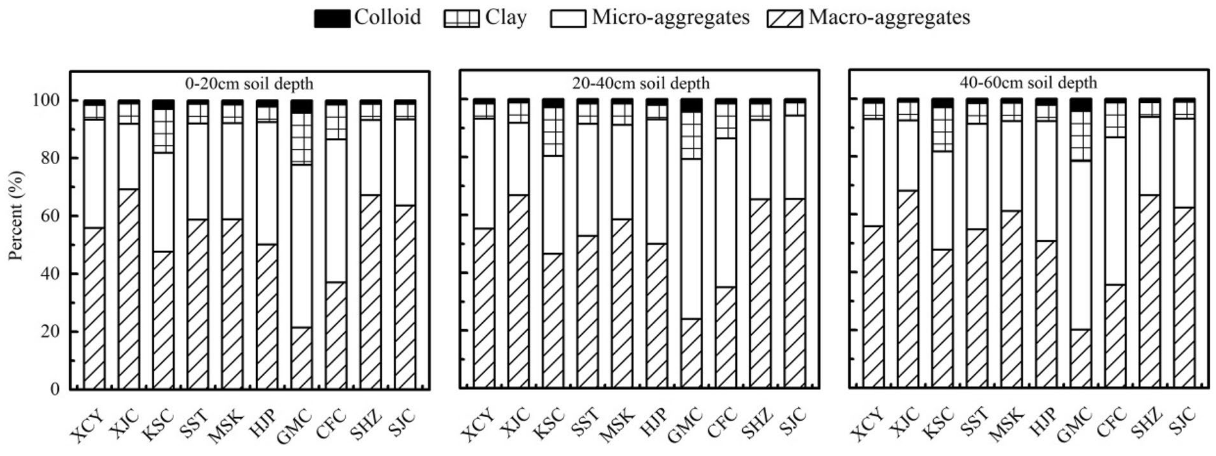

Fig. 2 Composition of soil aggregates in the original soils at 0–20, 20–40 and 40–60 cm depths

Table 2 Chemical properties of soil and contents of Cd and Pb in soil aggregates

Chemical property	Macro-aggregates	Micro-aggregates	Silt	Colloid
pH	$6.5^{b} \pm 0.7$	$6.6^{b} \pm 0.6$	$7.1^{ab} \pm 0.5$	$7.9^{a} \pm 0.5$
Organic matter (g/kg)	$22.0^{a} \pm 9.3$	$16.5^{a} \pm 10.1$	$25.1^{a} \pm 10.6$	$40.6^{a} \pm 18.3$
CEC (*c* mol/L)	$10.4^{a} \pm 2.4$	$10.8^{a} \pm 2.2$	$16.5^{a} \pm 2.9$	$52.1^{a} \pm 40.1$
Free iron oxide (mg/kg)	$36.6^{b} \pm 15.2$	$55.3^{b} \pm 19.2$	$96.2^{b} \pm 45.1$	$1265.3^{a} \pm 742.3$
Phosphorus (g/kg)	$1.5^{a} \pm 0.5$	$0.7^{b} \pm 0.5$	$1.0^{b} \pm 0.4$	$1.4^{a} \pm 0.3$
Total Cd (mg/kg)	$6.5^{b} \pm 3.2$	$3.8^{b} \pm 2.0$	$4.6^{b} \pm 3.1$	$96.2^{a} \pm 68.3$
Available Cd (mg/kg)	$1.2^{b} \pm 1.1$	$1.2^{b} \pm 1.2$	$1.6^{b} \pm 2.2$	$60.2^{a} \pm 45.2$
Total Pb (mg/kg)	$765.2^{b} \pm 986.4$	$469.5^{b} \pm 568.2$	$530.9^{b} \pm 650.4$	$6059.2^{a} \pm 10624.2$
Available Pb (mg/kg)	$90.3^{b} \pm 70.3$	$99.6^{b} \pm 103.3$	$68.3^{b} \pm 96.2$	$433.2^{a} \pm 605.2$

Using single factor analysis of variance and multiple comparison, different alphabets (a, b) means the value of the data has significant difference at the 5% levels, the same alphabet of the data has no significant difference in statistics

Table 3 Correlations between the chemical fractions of cadmium and lead and the soil properties

Heavy metals	Chemical fractions	pH	Organic matter (g/kg)	CEC (mol/kg)	Free iron oxide (mg/kg)	Phosphorus (g/kg)
Cd	EXC	− 0.302**	− 0.058	− 0.031	0.066	− 0.236**
	CA	− 0.133	− 0.098	− 0.015	− 0.017	− 0.042
	R_2O_3	0.058	− 0.052	− 0.105	− 0.133	− 0.272**
	OM	− 0.062	− 0.112	0.085	0.052	0.175*
	RES	0.182*	0.096	0.058	0.029	0.218**
Pb	EXC	0.133	0.209*	0.507**	0.609**	0.232**
	CA	0.076	− 0.063	0.067	0.006	− 0.152
	R_2O_3	− 0.039	− 0.032	− 0.178*	− 0.240**	− 0.348**
	OM	− 0.255**	− 0.066	− 0.075	− 0.118	0.018
	RES	− 0.023	− 0.402	− 0.158	− 0.132	0.166*

EXC, exchangeable fraction; CA, carbonate-bound fraction; R_2O_3, Fe–Mn oxide-bound fraction; OM, organic matter-bound fraction; RES, residue fraction

* $P < 0.05$, correlation

** $P < 0.01$, significantly correlation; $n = 180$

Thus, the macro-aggregate had the maximum contribution of total Cd, total Pb and available Pb. The colloid had the maximum contribution of available Cd.

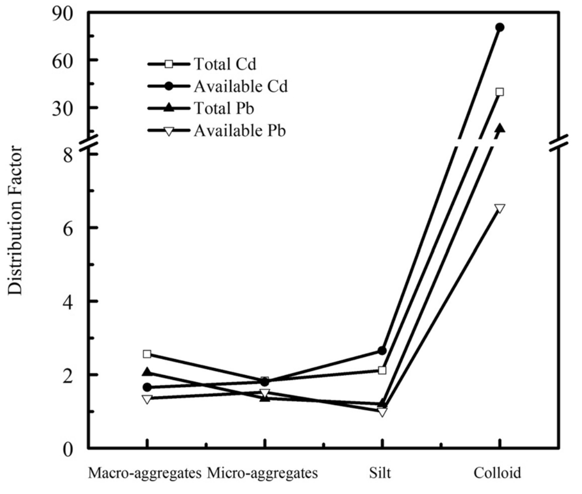

Fig. 3 Distribution factors of Cd and Pb in soil aggregates

Chemical fractions of cadmium and lead in soil aggregates

For the chemical fractions, both the Cd and Pb mainly existed as the residual fraction. The average percentages of residual Cd and Pb were 67.5 and 46.9%, respectively. Following these were the Fe–Mn oxide fraction and the exchangeable fraction. The proportions of the Fe–Mn oxide and exchangeable Cd were 10.6 and 9.8%, and those of Fe–Mn oxide and exchangeable Pb were 25.2 and 8.9%, respectively. Thus, the potential bio-available fractions of the Cd and Pb reached 22.7 and 44.3%, respectively (Fig. 5).

There were high distribution factors for the residual and exchangeable fractions of both Cd and Pb in the colloid.

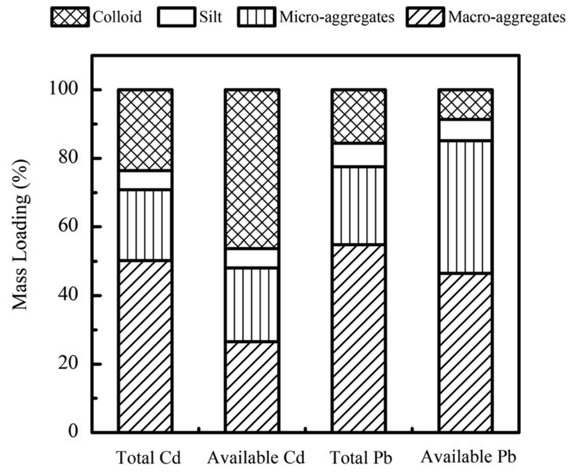

Fig. 4 Mass loading of Cd and Pb in soil aggregates

The distribution factors of the residual and exchangeable Cd were 55.9 and 33.0, and those of the residual and exchangeable Pb were 33.4 and 41.9, respectively (Fig. 6).

Correlations between fractions of cadmium and lead with chemical properties

There were very significant negative correlations ($P < 0.01$) between the pH and the exchangeable Cd content, phosphorus content and exchangeable and Fe–Mn oxide-bound fractions of Cd content and between the pH and the organic matter-bound fractions of Pb content, free iron oxide and phosphorus contents and the Fe–Mn oxide-bound fractions of Pb content. There was also a significant negative correlation ($P < 0.05$) between the CEC content and Fe–Mn oxide-bound fractions of Pb content (Table 3).

In addition, there were very significant positive correlations ($P < 0.01$) between the phosphorus content and the residual Cd content, the contents of CEC, and free iron oxide and between phosphorus and the exchangeable Pb content. There were also significant positive correlations ($P < 0.05$) between the pH and the residual Cd content, the organic matter content and the exchangeable Cd content, and the phosphorus content and the organic matter bond fractions of Cd content and the residual Pb content (Table 3). Therefore, the chemical fractions of both Cd and Pb were closely related to the chemical properties in soil aggregates of the polluted farmland.

Discussion

Characteristics of heavy metal and environmental effect in the surrounding farmland soil

The average contents of Cd and Pb in the present research were far higher than the national soil background content of China (Cd: 0.10 mg/kg; Pb: 26.00 mg/kg) and the background content of Yunnan province (Cd: 0.22 mg/kg; Pb: 40.60 mg/kg) (Zhao 1990) and were even higher in the 0–20 cm soil layer. Similarly, the contents of Cd and Pb in a mining area of Shanxi in China and in Slovakia were higher in the surface soil (Li et al. 2015b; Musilova et al. 2017). This occurred because mining areas contain a great deal of heavy metal-polluted dust, which will float down to the surrounding environment (Galiulin et al. 2002) and cause heavy metal pollution in the surface soil though wind and transport.

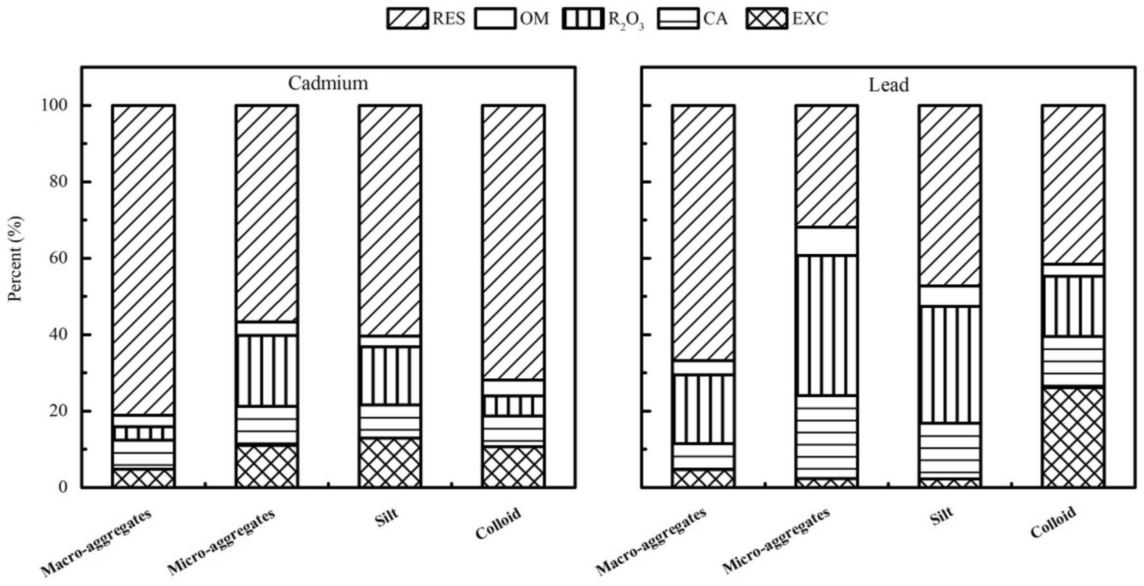

Fig. 5 The percentages of Cd and Pb fractions in soil aggregates

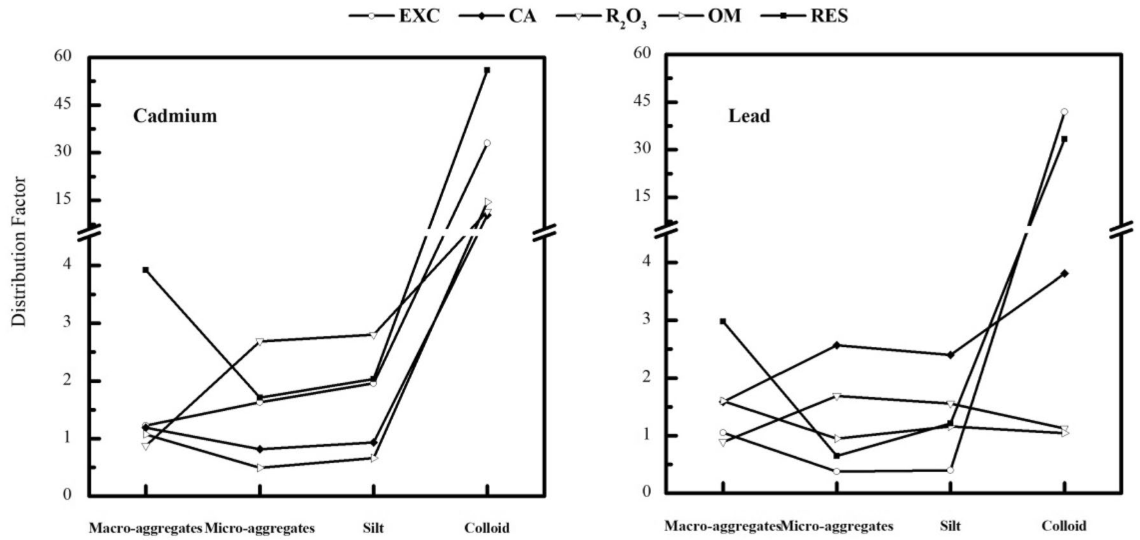

Fig. 6 Distribution factors of Cd and Pb fractions in soil aggregates

For the soil aggregates, both the total and effective Cd and Pb gather mainly in the macro-aggregates and colloid. Colloid has the highest distribution factor of the Cd and Pb. Studies on the relationship among urbanized areas, waste water and mining area soil present the same results, suggesting that Cd and Pb accumulate primarily in fine particles (Luo et al. 2011; Harter and Naidu 1995; Quenea et al. 2009). Macro-aggregates have the highest mass loading for Cd and Pb, followed by colloid and micro-aggregates, in a study of typical black and bog arable soils (Gong et al. 2012). This occurs because the heavy metal pollutants in the soil first adsorb on the macro-aggregate surface or because fine particles containing heavy metals gather to form large particle size aggregates (Acosta et al. 2011; Varrica et al. 2003). Smaller particle size soil aggregate shave a large specific surface and higher content of organic matter, CEC and free iron oxide; thus, the adsorption of more heavy metal and the existence of negative charge do not consume much of these aggregates (Sutherland 2003; Acosta et al. 2009).

Based on the dissolution, precipitation, coagulation and adsorption activity of heavy metals in the soil, different fractions of heavy metal will form and show different bio-availability(Kwonrae et al. 2009). Thus, compared to studies of forest and mine area soils, the Cd and Pb in the soils examined here existed mainly in the residual fractions (Gao et al. 2012; Li et al. 2015a). The residual fractions of heavy metal can stabilize in the sediments for a long time, are not easily released into nature and are difficult for plants to uptake (Lukowski and Wiater 2009). However, the potential bio-available fractions of the Cd and Pb were as high as 22.7 and 44.1%, respectively. The silt and colloid have higher distribution factors for the potential bio-available fractions of both Cd and Pb. The exchangeable and carbonate-bound fractions of heavy metal have greater mobility and are most likely released into the environment. The organic matter-bound fraction of a heavy metal has greater mobility in the oxidation environment and causes biological toxicity (Han et al. 2005).

The uptake of Cd and Pb as biological non-essential elements in crop sand into the food chain is a major hazard in farmland soil and causes security risks for human food that can cause chronic poisoning, liver and kidney damage and decreased bone metabolism (Aigberua et al. 2017; Arao et al. 2010). The health risk assessment of Cd and Pb in the Huize lead–zinc mine indicated that it poses significant potential health risks to children and that important consideration should be given to prevention (Liu et al. 2016). Because of the Pb in Yellow River water and Cd in spring wheat, the thorough consumption of vegetables indicated that the hazard index values of all heavy metals in the different function areas were higher than 10.0 and posed a high chronic risk to adults(Li et al. 2017; Qin et al. 2010). Therefore, the potential biological toxicity of a heavy metal in small particle size soil aggregates needs more attention in health risk assessment.

Correlation between soil properties and cadmium and lead fractions

The Cd and Pb fractions in soil aggregates have a significant relationship with the heavy metal bio-availability. The soil pH determined the solubility of various minerals and the ion adsorption in the solid phase (Gustafsson et al. 2012). In the present research, pH value had a significant negative correlation with the exchangeable Cd. With an increased pH value, the content of silt mineral decreased. The hydrated oxide and organic matter increased on the surface of soil. Because the H^+ concentration decreased, the competition of H^+ and Cd^{2+} on the adsorption point was reduced and decreased the content of exchangeable Cd (Unuabonah et al. 2009).

The organic matter, CEC and free iron oxide are important factors in soil heavy metal pollution and rely on specific adsorption and surface coordination (Fan et al. 2014). Additionally, a significant positive correlation with exchangeable Pb has been shown. Free iron oxide has a great specific surface area and chemical activity for the adsorption of heavy metals (Huang et al. 2002). CEC indicates the amount of negative charge in soil colloid. With increased CEC contents, the amount of negative charge increased. Additionally, it can provide more adsorption points for a heavy metal (Padilla-Ortega et al. 2011). Under the action of microorganisms, organic matter can form the soil humus. Additionally, it can form a combination of organic colloid and organic–inorganic compound colloid in the soil silt mineral to increase the soil surface area and surface activity, change the soil CEC contents and increase the capacity of soil to adsorb heavy metals (Regelink et al. 2011).

The phosphorus content had a significant negative correlation with the exchangeable and residual fractions of Cd. The increased phosphorus content made heavy metal ions and phosphate ions form stable sediment in soil and caused the potential available fractions to transform into the non-useful residual fraction (Cao et al. 2009; Gullap et al. 2014; Peter et al. 2011). The phosphorus content also had a very significant positive correlation with the exchangeable Pb. The nutrient of farmland soil may be controlled by many factors, but the mechanism of phosphorus on the heavy metal fraction remains unclear.

We observed that the farmland soil around the Huize lead–zinc mine has serious Cd and Pb pollution. The macro-aggregate has the maximum mass loading, and colloid has the highest distribution factor for Cd and Pb. Heavy metals in small particle size soil aggregates have higher potential biological toxicity. The Cd and Pb fractions have close relationships with the soil chemical properties. However, the relationship between heavy metals and soil chemical properties is not yet clear and needs further study.

Conclusions

In the seriously polluted area around the lead–zinc mine, soil aggregates accounted for most of the macro-aggregates, not the colloid, at three depths. The contents of organic matter, cation exchange capacity, free iron oxide, Cd and Pb increased as the particle size decreased in soil aggregates. The macro-aggregate had a maximum loading mass, and the colloid had the highest enrichment of Cd and Pb. Both Cd and Pb mainly existed as residual fractions, and their fractions closely correlated with the soil chemical properties. However, the enriched distributions of Cd and Pb in the colloid easily migrated and could be a potential hazardous source in the soil.

Authors' contributions

MYZ and ZFD have made contributions in the acquisition of the data, data collection, data coding and entry, data analysis, interpretation of the result. LY has been involved in critically advising, revising the manuscript and made possible suggestion. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

Not applicable.

Consent for publication

Not applicable.

Ethics approval and consent to participate

Not applicable.

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