

Spatial distribution of soil cadmium and its influencing factors in peri-urban farmland: a case study in the Jingyang District, Sichuan, China

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Abstract Semi-agricultural ecosystems in peri-urban areas are susceptible to contamination. The spatial distribution and influencing factors of such pollution are unclear and poorly constrained in many areas worldwide. Therefore, studying the problems of soil pollution in peri-urban areas is critical for environmental management and agricultural production. In this paper, with cadmium (Cd) as the target pollutant, the spatiotemporal variations of soil cadmium pollution and the relative importance of the affecting factors were analyzed at a peri-urban area from the Jingyang District, Sichuan, China. Statistical results showed that the farmland in the study area could be considered moderately soil Cd-polluted, under the dual influence of natural factors and human activity. In particular, the soil Cd concentration in Tianyuan and Bajiaojing exceeded 0.5 mg kg^{-1} , for intensive industrial enterprises are distributed in these areas. Correspondingly, the geoaccumulation index also showed that the contamination of Cd in this area was moderately polluted. Moreover, the ecological risk index was 80% in the study area, indicating that the soil Cd pollution potential risk was moderate to high. High geological background values (soil Cd = 0.29 mg kg^{-1}),

river migration, industrial enterprises, and traffic significantly influenced soil Cd pollution, with natural geological factors playing greater roles. The significant horizontal-spatial effective distances away from Shiting River, Deyang-Aba Highway, and chemical plants were 200, 400, and 100 m, respectively. These results will be useful in guiding farmland cultivation and pollution remediation effectively in the peri-urban areas.

Keywords Soil cadmium · Spatial distribution · Influencing factors · Peri-urban area

Introduction

Cadmium (Cd) has accumulated in soil due to rock weathering and human activity, although it has been difficult to discern the relative contributions of these influences, particularly in heavily polluted environments (Valdés et al. 2005). Both industrialization/urbanization (such as industry, agriculture, and traffic) and natural geological processes can induce severe heavy metal pollution in some farmland soils (Zhao et al. 2008; Shi et al. 2012; Chrastný et al. 2012; Lin et al. 2011; Li et al. 2014a). To date, human activity has played a role in heavy metal pollution, due to its uneven spatial distribution (Zhang et al. 2009a, b; Shan et al. 2013; Creuzer et al. 2016). In previous studies, the spatial distribution of pollutants has been used to identify a region's pollution status and can be used as the evidence for pollution abatement measures (Chiang et al. 2011; Ağca and Özdel 2014). Thus, although

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regional changes in soil pollution have been mapped, low sample density has made it difficult to detect small-scale changes in heavy metal pollution and its driving factors.

In recent years, several studies have been conducted in peri-urban areas (especially in China) (Hua et al. 2014; Wang et al. 2014; Chen et al. 2008), which were small in scale and semi-agricultural or industrial soil ecosystems (Huang et al. 2006). Peri-urban areas are subject to intensive land use as they connect rural and urban areas. Such land use may increase the risk of heavy metal pollution (Zhao et al. 2007; Luo et al. 2012). A peri-urban area (Deyang City) in the Chengdu Plain has received widespread attention due to its heavy metal pollution in water, soil, and rice (Li et al. 2014b). As a result of geological processes and intense human activity (including industry and traffic), the farmland in this area has been exposed to high levels of soil Cd pollution, although the small-scale distribution of this pollution has not yet been clarified (Huang et al. 2008). Previous studies have discussed the influences of soil cadmium pollution from soil parent material (Zhu 2001; Romić and Romić 2003; Wang et al. 2011), soil type (Zhao et al. 2007; Luo et al. 2012; Li et al. 2013), water system (Zhu 2001; Yang et al. 2010; Liu and Yu 2012), atmospheric deposition (Okin et al. 2009; Gallon et al. 2011), and human activities (traffic emission, industrial emission, etc.) (Pelletier 2006; Xie et al. 2007; Csavina et al. 2011; Filippelli et al. 2012). However, because the relative importance of different factors is often region-specific, deeper analysis is necessary regarding the extent and range influences of these factors on soil Cd pollution, which can contribute to environmental management and agricultural production.

This study was conducted in a peri-urban area of the Jingyang District, Deyang City, to (1) investigate soil Cd concentration in the farmland and assess the Cd contamination level and potential ecological risk; to (2) assess the spatial distribution patterns of soil Cd pollution in the study area; and to (3) analyze the source of cadmium in peri-urban soil from soil parent materials, river migration, transportation action, and industrial enterprise emissions, which will contribute to a deep understanding of the mechanism of cadmium pollution in the study area. Information obtained from this study will provide support for regional prevention and control of soil Cd pollution in peri-urban farmland.

Materials and methods

Study area

The study area was located in the Jingyang District (Deyang City) in the upstream reaches of the Tuojiang River Basin, covering an area of 648 km² and spanning a range of geographic coordinates from 104° 14' 55" E to 104° 33' 02" E and from 31° 04' 57" N to 31° 20' 23" N. This area experiences a subtropical humid monsoon climate, with neither cold winters nor hot summers. The annual average temperature is 16.1 °C, and the frost-free season is long. The annual average precipitation is 893 mm, with 1251.5 h of sunshine annually. The terrain varies between the northwest and southeast areas, with higher elevations in the range of 457–764 m in the northwest.

Twelve major soil types can be found in the study area and are defined based on the Chinese soil taxonomy classification (GB/T17296-2009) (AQSIQ 2009), including paddy soils, purplish soils, fluvo-aquic soils, yellow earths, skeletal soils, and alluvial soils. Two crops (rice and wheat/rapeseed) are planted each year in most parts of this area.

The Tuojiang River is the major river running through the study area from west to east, and its main tributaries include the Shiting and Mianyuan Rivers. Holocene gray-brown alluvium and Upper Pleistocene Series old yellow alluvial clay form the flat areas, whereas purple sands/shales exhibiting efflorescence from the Late Cretaceous and the Jurassic Penglaizhen Formation form the hilly areas. The upstream reaches of the Tuojiang River host many mineral resources, including phosphate ore, natural gas, limestone, and coal. Accordingly, mineral resource exploitation in this region has had a significant influence on the agricultural soils of the Jingyang District. Agriculture is well developed in the study area, particularly for cereal, oil, fruit, pigs, poultry, and other high-quality agricultural products. Moreover, the industrial economy is considerably important in the area, accounting for more than 60% of the gross domestic product (GDP), with world-renowned manufacturers, including the China National Erzhong Group and the Dong Electrical Machinery Co., Ltd., located in the Jingyang District. Transport infrastructure is also well developed, with a road density of 1.41×10^2 km km⁻² and passenger and freight turnover accounting for approximately 30% of Deyang City.

Soil sampling and laboratory analysis

Soil samples were selected to be representative of the variation in all natural factors in the study area, particularly soil parent material and soil type, and sample density was highest near rivers, industrial plants, and roads. In total, 149 soil samples were collected from the arable layer (i.e., the top 0–20 cm); 68 of these were from non-irrigated farmland and 81 were from paddy fields. All soil samples were located by GPS (Fig. 1). Soil samples of “old walls,” which were used to build the old house walls, could be considered to represent the soil background value. Soil Cd concentration was analyzed from “old walls” ($n = 5$) dating from the 1960s and 1970s in the Jingyang District to reflect the soil Cd pollution source. The collection points of the “old wall” soil samples were distributed in Tianyuan, Hexin, and Xiaogan of the Jingyang District (Fig. 1).

To investigate the factors influencing soil Cd pollution, soil samples were collected at particular distances from typical rivers, roads, and chemical plants. Near the chemical plants (Meifeng and Yuanfeng Chemical Ltd.), soil samples

were collected across a fan-shaped area at distances of 0–5, 5–10, 10–50, 50–100, and 100–400 m from the discharge point. Along the Deyang–Aba Highway, National Road 108[#] (G108), and the Chengdu–Mianyang Highway, samples were collected 1, 5, 8, 10, 20, 50, 80, 100, 200, and 400 m from the shoulder. Near the Shiting River, samples were collected from the flood plain at distances of 5, 10, 20, 50, 100, 200, 500, 1000, and 1500 m from the bank (Fig. 2).

Soil samples were collected from each plot using a five-point sampling method and then air-dried. The soil samples were subsequently passed through 18- and 100-mesh sieves and then used for physical and chemical fraction analysis and heavy metal concentration analysis. Soil samples were digested using a HNO₃–HF–HClO₄ (2:2:1, v:v:v) solution at a 1:25 soil to liquid ratio to determine the total Cd concentration (Lu 2000). The Cd concentration of the samples was determined using an atomic absorption spectrophotometer (Agilent 7700X, Agilent, USA). A certified standard Cd solution obtained from the National Research Center for CRM, China, was used to ensure the precision of the analytical procedures (GBW07403).

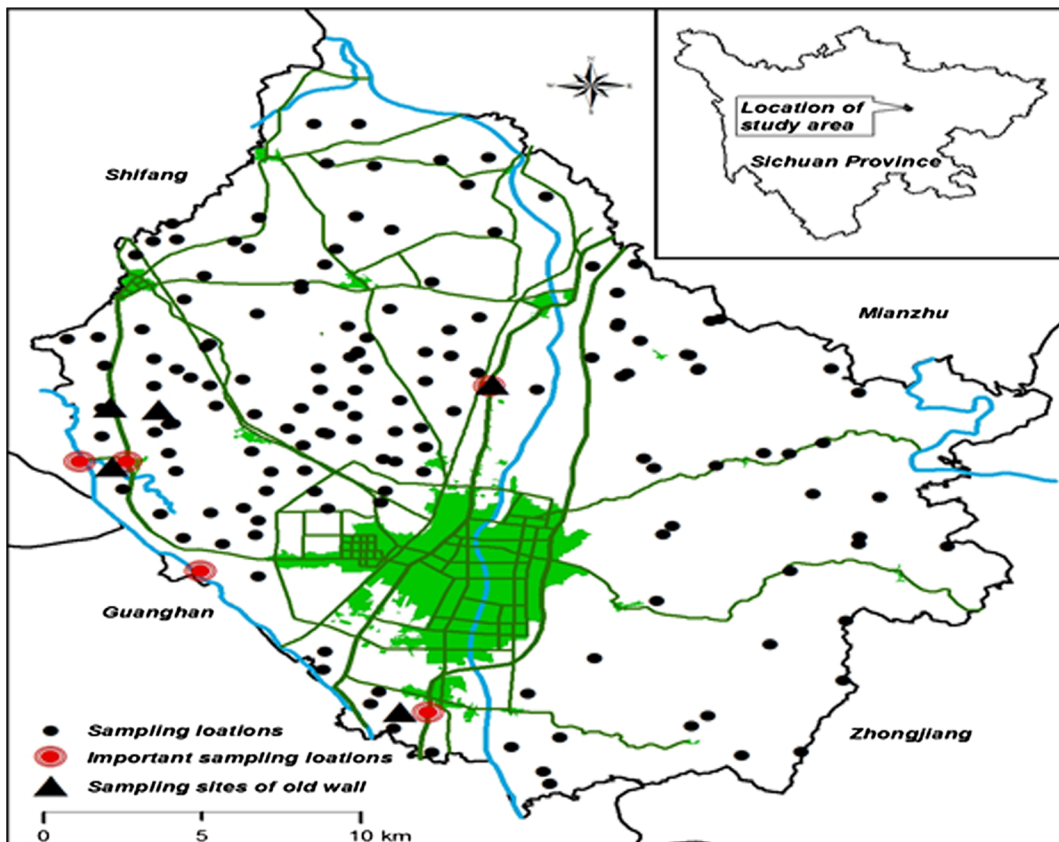


Fig. 1 Soil sample distribution in peri-urban areas (Jingyang District, Deyang City, Sichuan, China)

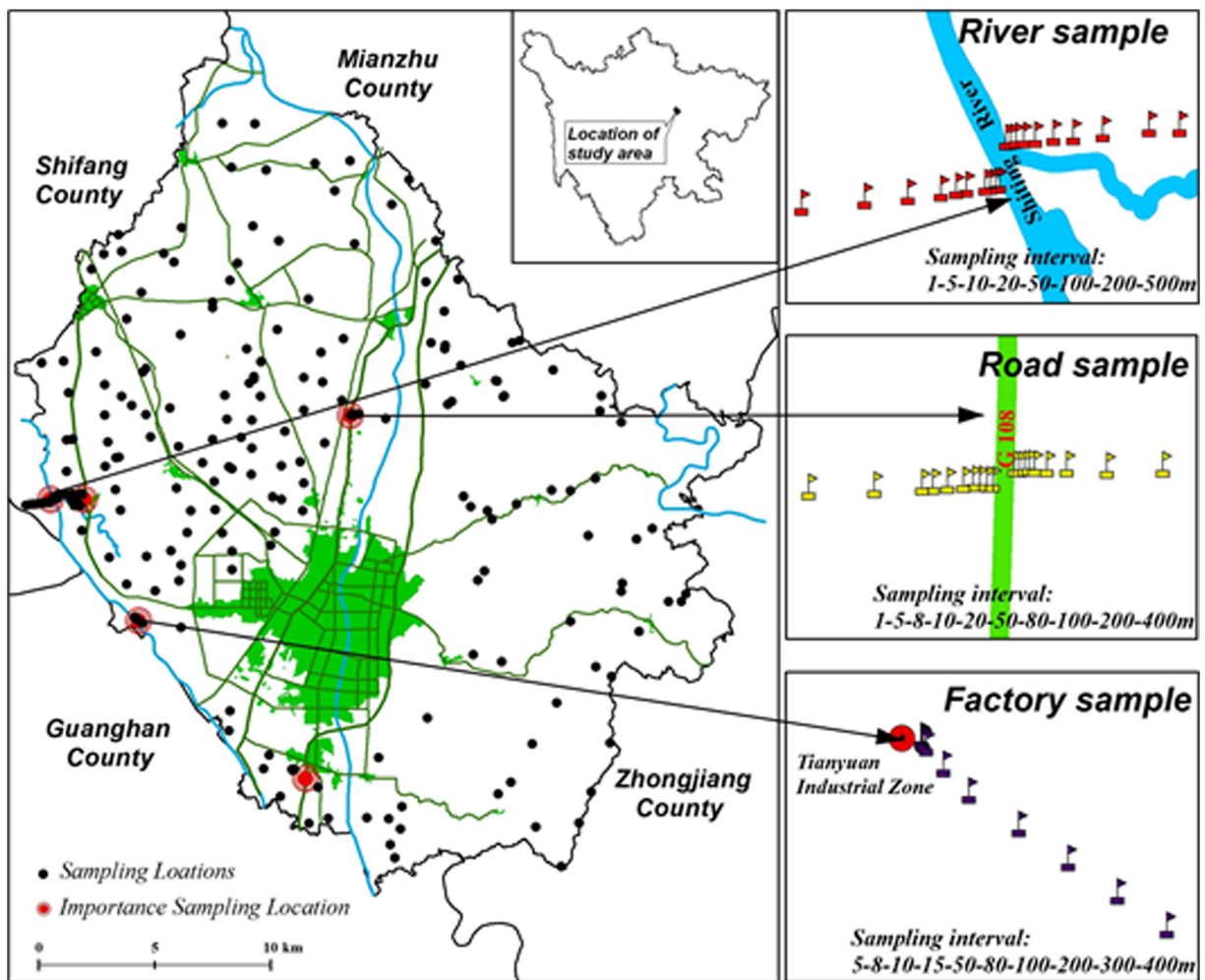


Fig. 2 Distribution of soil samples in the area of pollution source monitoring

Soil Cd pollution evaluation

Geoaccumulation index

The geoaccumulation index (I_{geo}) was used to assess the Cd contamination level of farmland soils and was calculated according to the following equation (Shi et al. 2014):

$$I_{geo} = \log_2 \left[\frac{C_n}{KB_n} \right] \tag{1}$$

Table 1 National Environmental Quality Standards (EQS) of soil Cd pollution (GB15618-1995) (SPAC1995)

EQS grade	Grade I	Grade II	Grade III		
Soil pH	–	<6.5	6.5–7.5	>7.5	>6.5
Cd ($\leq \text{mg kg}^{-1}$)	0.20	0.30	0.30	0.60	1.00

where C_n is the measured concentration of Cd (milligrams per kilogram) in soils, B_n is the geochemical background concentration of Cd (milligrams per kilogram) in soils, and the constant $K = 1.5$ is a correction coefficient that helps account for natural fluctuations and anthropogenic influences (Shi et al. 2014). The values of I_{geo} were classified as follows: uncontaminated ($I_{geo} \leq 0$), uncontaminated to moderately contaminated ($0 < I_{geo} \leq 1$), moderately contaminated ($1 < I_{geo} \leq 2$), moderately to heavily contaminated ($2 \leq I_{geo} < 3$), heavily contaminated ($3 \leq I_{geo} < 4$), heavily to extremely contaminated ($4 \leq I_{geo} < 5$), and extremely contaminated ($I_{geo} \geq 5$) (Shi et al. 2014).

Table 2 Descriptive statistics of soil Cd concentration in towns of the Jingyang District

Town	Samples (n)	Mean (mg kg ⁻¹)	Standard deviation (mg kg ⁻¹)	Minimum (mg kg ⁻¹)	Maximum (mg kg ⁻¹)	Coefficient of variance (%)
Shuangdong	10	0.22	0.05	0.16	0.29	21.16
Hexin	6	0.24	0.03	0.22	0.29	11.82
Xinzhong	5	0.26	0.04	0.21	0.33	16.72
Donghu	4	0.27	0.05	0.21	0.32	17.90
Huangxu	22	0.32	0.15	0.14	0.68	48.80
Dexin	17	0.40	0.11	0.19	0.55	27.38
Xiaoquan	17	0.43	0.20	0.19	1.13	46.15
Xiaogan	17	0.44	0.17	0.17	0.77	38.91
Yangjia	18	0.47	0.16	0.17	0.76	34.32
Bolong	5	0.48	0.30	0.18	0.93	63.59
Tianyuan	17	0.51	0.27	0.18	1.42	52.38
Bajiaojin	11	0.53	0.18	0.25	0.94	34.96

Potential ecological risk index

The ecological risk index (E_r) was calculated as follows (Liu et al. 2015):

$$E_r = \frac{C_i}{B_i} T_i \tag{2}$$

where C_i is the measured concentration of Cd (milligrams per kilogram) in soils, B_i is the geochemical

background concentration of Cd (milligrams per kilogram) in soils (based on Table 1), and T_i is the toxic factor, which was assumed to be 30 for Cd (Liu et al. 2015). Then, E_r was classified as follows: low potential ecological risk ($E_r < 40$), moderate potential ecological risk ($40 \leq E_r < 80$), considerable potential ecological risk ($80 \leq E_r < 160$), high potential ecological risk ($160 \leq E_r < 320$), and very high potential ecological risk ($E_r \geq 320$) (Liu et al. 2015).

Table 3 Descriptive statistics of soil Cd concentration in different soil types

Soil types	Samples (n)	Mean (mg kg ⁻¹)	Standard deviation (mg kg ⁻¹)	Range (mg kg ⁻¹)	Coefficient of variance (%)
Brown-purple gravel soil	19	0.30	0.12	0.14~0.52	41.58
Gravelly purple soil	6	0.43	0.27	0.18~0.93	62.47
Yellow-red-purple sand-silt soil	10	0.26	0.04	0.21~0.33	14.87
Small yellow sand-silt soil	9	0.48	0.18	0.22~0.74	38.02
Brown-purple-yellow silt soil	5	0.24	0.02	0.20~0.26	10.03
Gray-brown alluvial sand-silt soil	19	0.42	0.14	0.18~0.68	34.79
Gray-brown sandy paddy	7	0.40	0.19	0.19~0.76	47.59
Gray-brown alluvial silt paddy	38	0.49	0.21	0.17~1.13	42.64
Purple alluvial sand-silt paddy	5	0.44	0.07	0.34~0.54	16.96
Purple alluvial silt paddy	8	0.19	0.03	0.16~0.21	14.93
Shallow yellow silt paddy	6	0.24	0.04	0.21 ~ 0.29	18.16
Yellow silt paddy	17	0.45	0.22	0.17 ~ 1.42	48.01

Note: The soil types named by “Classification and codes for Chinese soil (GB/T17296-2009)” (AQSIQ 2009)

Table 4 Descriptive statistics of soil Cd concentration for different land-use types

Land-use types	Range (mg kg ⁻¹)	Mean (mg kg ⁻¹)	Variable coefficient (%)	Over background values ^a (±%)
Old wall ^a	0.16–0.39	0.29 ± 0.09	30.44	–
Bamboo	0.28–0.78	0.61 ± 0.20	32.45	100.10
Vegetable	0.34–0.68	0.50 ± 0.15	29.65	71.03
Wheat	0.32–0.56	0.41 ± 0.09	21.71	42.76
Rapeseed	0.39–0.58	0.48 ± 0.07	14.75	64.13
Rice	0.28–0.76	0.44 ± 0.20	44.84	53.10

The number of soil samples in the different land-use types was 30

^a Old wall soil was the retaining wall in the 1960s–1970s and was named as the background values

Statistical and geostatistical analysis

Descriptive statistics were produced and correlation analysis was conducted using Excel 2010 and SPSS 13.0. The sampling points, defined precisely by GPS, were integrated using ArcGIS v.10.0 to create a database in which the coordinates and analytical values of each point were included. Spatial interpolation and GIS mapping techniques were employed to produce spatial distribution maps of soil Cd concentration and pollution evaluation results in ArcGIS v.10.0. In ArcGIS, the ordinary kriging method was used, which can express the spatial variation and allow a variety of map outputs while minimizing the errors of predicted values.

In the main controlling factor analysis of soil Cd pollution in peri-urban farmland, deviation and regression analyses were used to investigate the influence of various factors on soil Cd concentration by SPSS 13.0. For soil parent material and soil type, quantitative variables were assigned dummy variables (Li et al. 2014a). By adjusting the coefficient of determination in the regression analysis, the extent was assessed of each factor's ability to affect soil Cd concentration independently.

Table 5 Semi-variogram models and their parameters for soil Cd in the study area

Model	Nugget	Sill	Sill	Range (km)	R ²	RSS
Gaussian	0.107	0.268	0.399	21.50	0.929	0.005

Results and discussion

Statistical characteristics of soil cadmium

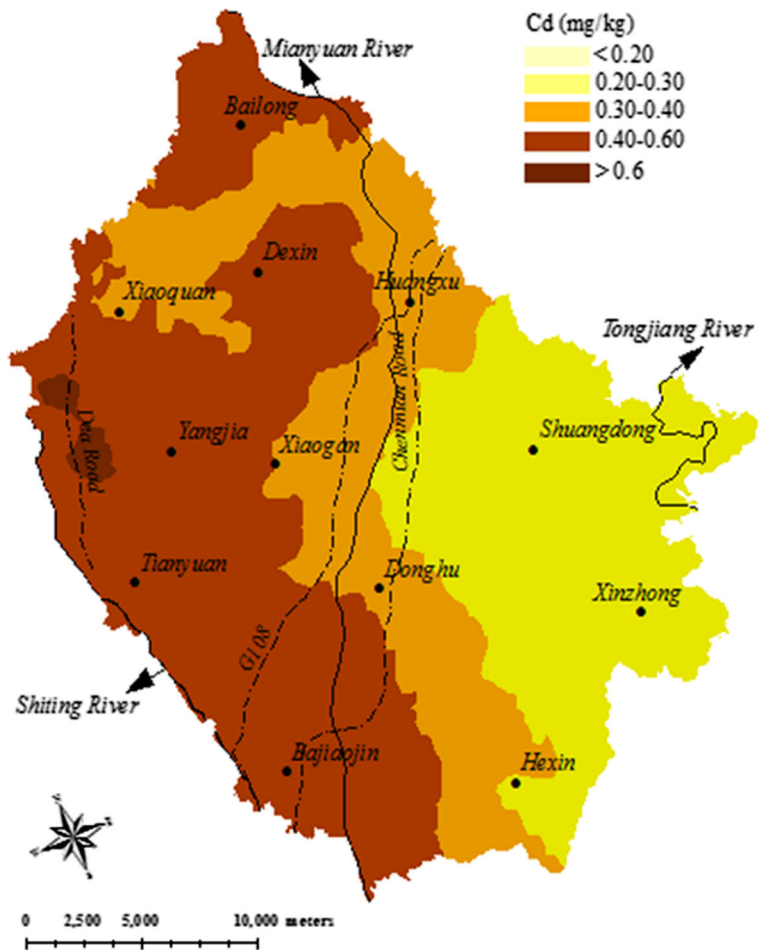
The soil Cd concentration in the farmland exceeded grade I of the National Environmental Quality Standards (EQS) for Soil Pollution (GB15618-1995) (SPAC 1995). The soil Cd concentration varied within and between towns. In Tianyuan and Bajiaoqing, the farmland soil Cd concentration exceeded 0.5 mg kg⁻¹, which was close to the double of grade II (GB15618-1995). The soil Cd concentration in Tianyuan exhibited the greatest variation, with a range of 1.24 mg kg⁻¹. The coefficient of variation varied by more than 40% between Bolong, Tianyuan, and Xiaoquan (Table 2). These towns particularly had developed industries with busy traffic and a well-developed road network. These results illustrated the randomized features associated with the influence of human activity under analogous geological conditions (Wang et al. 2012).

The “old walls” ($n = 5$) dating from the 1960s and 1970s in the Jingyang District exhibited a soil Cd concentration of 0.29 ± 0.09 mg kg⁻¹, exceeding grade I and almost reaching grade II of the EQS (pH 6.5–7.5, Cd ≤ 0.3 mg kg⁻¹). These “old walls” can be considered to represent the soil background value. Thus, the results presented that, other than human activity, soil parent material and soil type also contributed to the high levels of soil Cd pollution in this study area.

In terms of soil types, soil Cd concentration was relatively high in the gray-brown alluvial silt (0.49 ± 0.21 mg kg⁻¹), purple alluvial sand-silt (0.44 ± 0.07 mg kg⁻¹), and gray-brown sandy (0.40 ± 0.19 mg kg⁻¹) paddy field (Table 3). Soils with high Cd concentration were likely produced from purple rock outcropping locally and river sediment, suggesting that geological factors may lead to the accumulation of soil Cd in this region (Wang et al. 2007b; Wang and Liu 2013). However, because the landscape in this region was relatively flat and enterprises were concentrated in certain point location, the emission of industrial wastes and their dry and wet deposition were assumed to be the primary sources of soil heavy metal pollution (Tang et al. 2007a, b).

Soil Cd concentrations in some rain-fed croplands were relatively high, with small coefficients of variation for the small yellow sand-silt (0.48 ± 0.18 mg kg⁻¹), gravelly purple (0.43 ± 0.27 mg kg⁻¹), and gray-brown alluvial sand-silt soil (0.42 ± 0.14 mg kg⁻¹). This land-use type was distributed primarily in hilly areas far from

Fig. 3 Spatial distribution of soil Cd concentration in the Jingyang District



industrial enterprises and with a low road density. Therefore, in these areas, soil Cd accumulation can be attributed primarily to natural factors such as rock weathering and soil parent material (Wang and Liu 2013).

The “old walls” of the 1960s to the 1970s were used as a background value; agricultural land (e.g., vegetable, wheat, rapeseed, and rice fields) has experienced increases in soil Cd concentration in recent decades. Vegetable fields had higher soil Cd pollution (71.03% greater than the background value), followed by rapeseed fields (64.13% greater than the background value) (Table 4). These results suggested that cropping pattern and nutrient management were other important factors controlling soil Cd accumulation in farmland (Tang et al. 2007a, b).

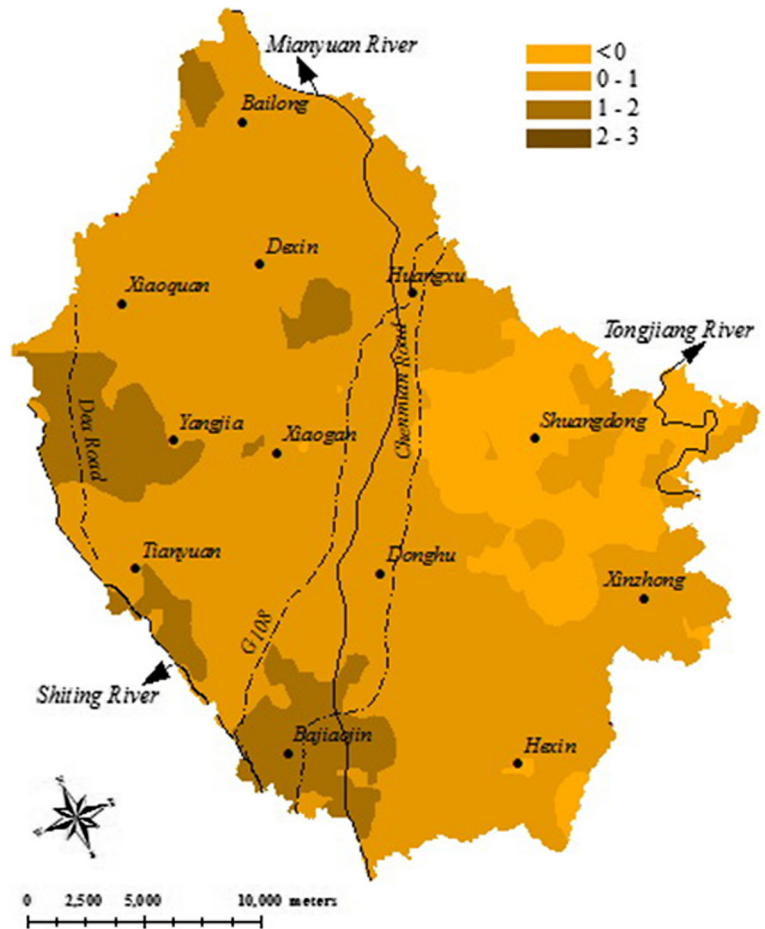
Scattering bamboo in agricultural areas can both protect farmland and serve as an important resource. Because bamboo was free from fertilizers and cultivation measures, these areas can intercept pollutants

deposited via atmospheric sedimentation. Accordingly, soil Cd concentrations in bamboo areas were found to be twice the background value. Compared to the soil Cd concentration in bamboo and agricultural land (Table 4), the bamboo planting can intercept exogenous Cd sources accumulated in farmland soil, which may be used as a soil Cd pollution prevention measure.

Semi-variance analysis

Results of semi-variance analysis are shown in Table 5. The experimental semi-variogram of soil Cd could be well fitted with the Gaussian model, which showed the highest R^2 value of 0.929. The range was 21.5 km, suggesting that soil Cd in this area has a relatively large range of spatial autocorrelation. The nugget to sill ratio of the semi-variogram model can be regarded as a criterion for classifying the spatial dependence for a variable. The degree of

Fig. 4 Evaluation of soil Cd based on the geoaccumulation index in the Jingyang District



spatial dependence can be considered strong, moderate, or weak if the ratio is equal to or lower than 0.25, between 0.25 and 0.75, and greater than 0.75, respectively. In this study area, the nugget to sill ratio of soil Cd was 0.399, suggesting that soil Cd had a moderate spatial dependence and that the spatial distribution of soil Cd was controlled by both intrinsic factors and extrinsic factors.

Spatial distribution characteristics of soil cadmium

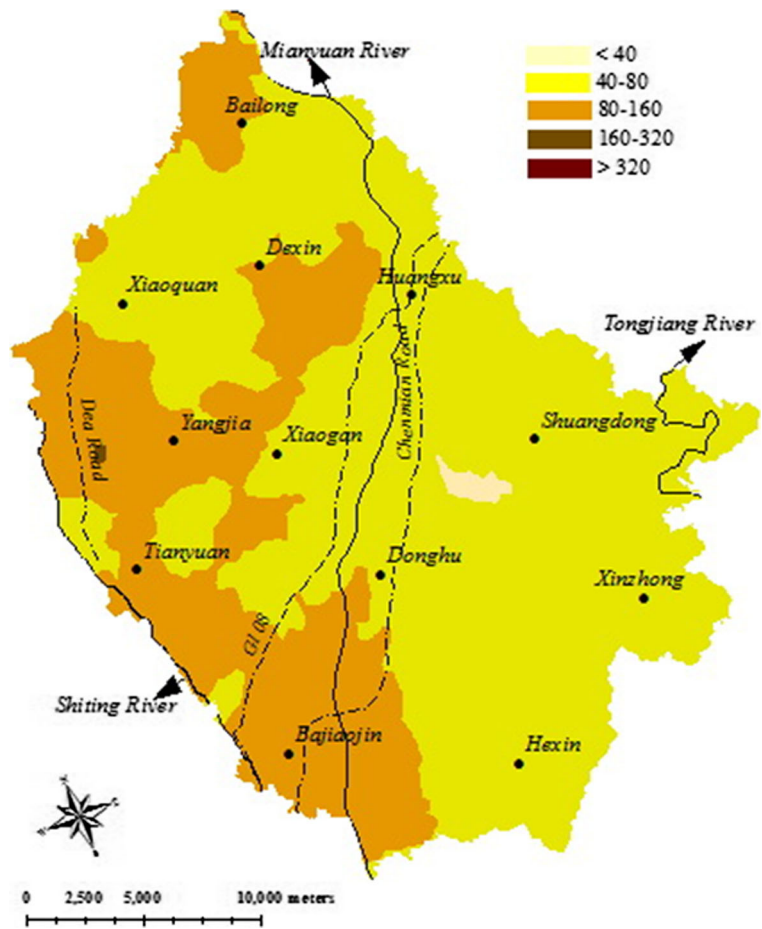
The soil Cd concentration in half of the study area was approximately 0.4–0.6 mg kg⁻¹ (Fig. 3), which corresponds to the moderate pollution category. The soil Cd pollution was found in the downtown areas of the Jingyang District, Shifang County, Mianzhu County, and the borders of Guanghan County. These areas hosted high densities of roads (e.g., National Road 108[#], the Deyang–Aba Highway, and the Chengdu–Mianyang Highway), rivers (i.e., the Shiting River and Mianyuan

River), and industrial enterprises (e.g., China National Erzhong Group, Dongqi Group, sewage treatment plants, and chemical plants) that had high levels of human activity (Figs. 1 and 2). Soil Cd concentration exceeding 0.6 mg kg⁻¹ was found primarily in Tianyuan and Yangjia, near Shifang County. The Shiting River runs through this area and is home to many chemical plants. Unregulated industrial wastewater emission resulted in pollution of the river, and the polluted water flowed into the surrounding farmland. Thus, it was necessary to supervise the emission of industrial wastes from chemical plants in this region, with a particular focus on the discharge of polluted water to the upstream reaches of Shiting River (Liu and Yu 2012; Tang et al. 2007a, b).

Soil Cd pollution evaluation

More than 50% of farmland in the Jingyang District exhibited I_{geo} in the range of 0–1, and more than 30% of the

Fig. 5 Evaluation of soil Cd based on the Hakanson potential ecological risk index in the Jingyang District



farmland exhibited I_{geo} in the range of 1–2 (Fig. 4). These results showed that this area was moderately polluted and lightly influenced by human activity. Only a few soil samples indicated moderate to high pollution levels ($2 \leq I_{geo} < 3$), and these were scattered within Tianyuan and Xiaoquan. The farmland soil Cd pollution in the Jingyang District exhibiting moderate to high potential ecological risk (E_r) accounted for 80% (Fig. 5). However, little farmland (5%) exhibited high potential ecological

risk. These areas were focused in the towns of Tianyuan, Bajiaojing, Xiaoquan, and Bolong.

Overall, human activity was found to exert light influence on the index of geoaccumulation, causing only slight to moderate pollution. Conversely, the potential ecological risk posed a considerable threat. In other words, soil Cd pollution in farmland may be due primarily to the geological background. The background values obtained from the “old walls”

Table 6 Effect of parent material on soil Cd concentration in farmland of the Jingyang District

Parent material	Samples (n)	Mean (mg kg^{-1})	Standard deviation (mg kg^{-1})	Range (mg kg^{-1})	Variable coefficient (%)
Slope wash	21	0.28	0.09	0.16–0.52	33.05
Saprolite	18	0.32	0.23	0.14–1.13	71.69
Chengdu clay	47	0.44	0.20	0.17–1.42	45.49
Alluvial deposit	63	0.44	0.18	0.17–0.94	40.09

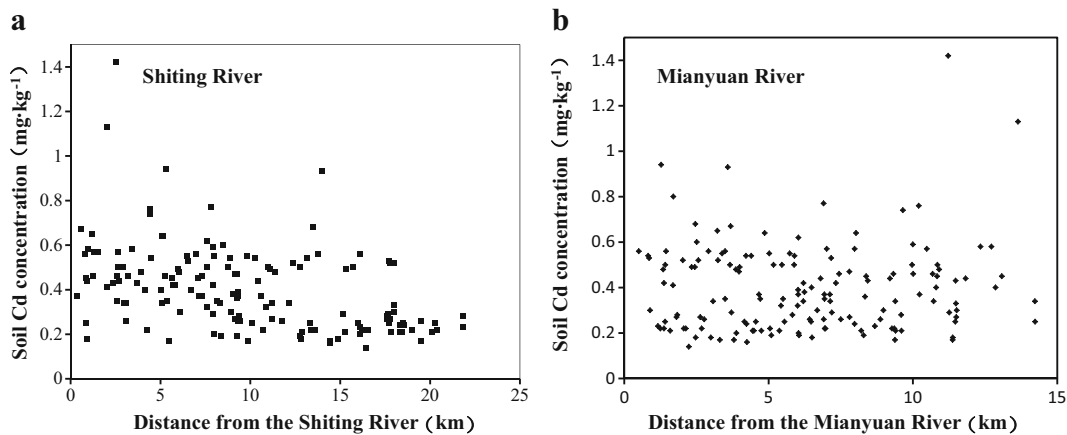


Fig. 6 Scatter plot of soil Cd concentration and distance from the main river. **a** Shiting River. **b** Mianyuan River

(Cd = 0.29 mg kg⁻¹) exceeded grade I of the EQS, almost reaching grade II. Therefore, the farmland in the Jingyang District can be considered moderately soil Cd-polluted, under the dual influence of natural factors and human activity. Accordingly, it was necessary to reveal the influencing factors and effect extent on soil Cd pollution to design prevention and control measures in peri-urban farmland.

Influencing factors on soil Cd pollution

Soil parent material

The soil parent materials in the Jingyang District include the quaternary gray-brown alluvium, old

yellow alluvium, quaternary loess-like deposits rich in calcium, yellow clay (i.e., Chengdu clay), and various lower cretaceous rock series (Soil survey office of Deyang County 1983). Soil that was sourced from slope wash (Cretaceous rocks) contained small amounts of soil Cd, lower than or similar to the background value of the “old walls” (0.29 ± 0.09 mg kg⁻¹) and with a small coefficient of variation.

From Table 6, it can be seen that old alluvium of the Salawusuan Stage of the Upper Pleistocene and more recent (i.e., Holocene) river sediments were distributed primarily within the first or second terraces of Chengdu Plain, which contained more soil Cd than the rain-fed cropland, likely owing to the purple Cretaceous stratum outcropping in this region. The yellow silt paddy, which was developed from old alluvium of Chengdu clay, contained 27.4% clay particles (<0.001 mm) and 20.6% sandy particles (0.05–1 mm). While, the gray-brown alluvial silt paddy (developed from alluvial deposit) has 15.6% clay particles and 31.7% sandy particles. Thus, although both of the soil types developed from different alluviums and differed in soil particle composition and soil texture, the soil Cd concentration was similar, and the coefficients of variation exceeded 40% (Table 3). This finding suggests that the influence of parent material on soil Cd accumulation in farmland was undermined by other influencing factors in the peri-urban area, where human activity may have an extensive impact.

River migration

Based on the spatial data vectorization, the distance from each soil sampling point to the rivers in the study area (i.e.,

Table 7 Concentration of Cd in soils alongside the Shiting River

Distance from river (m)	Northeast	Southwest
Wash land	0.53 ± 0.02a	0.52 ± 0.03a
5	0.52 ± 0.01ab	0.52 ± 0.02a
10	0.48 ± 0.01cd	0.48 ± 0.01b
20	0.49 ± 0.01cd	0.47 ± 0.01b
50	0.50 ± 0.01bcd	0.48 ± 0.03b
100	0.44 ± 0.03ef	0.48 ± 0.01b
200	0.45 ± 0.02ef	0.42 ± 0.01c
500	0.41 ± 0.03f	0.41 ± 0.03c
1000	0.46 ± 0.01de	0.44 ± 0.01c
1500	0.50 ± 0.03abc	0.44 ± 0.02c

Note: The number of soil samples at different distances was ten. Means with the same letter do not differ significantly at $p < 0.05$ using T-tests

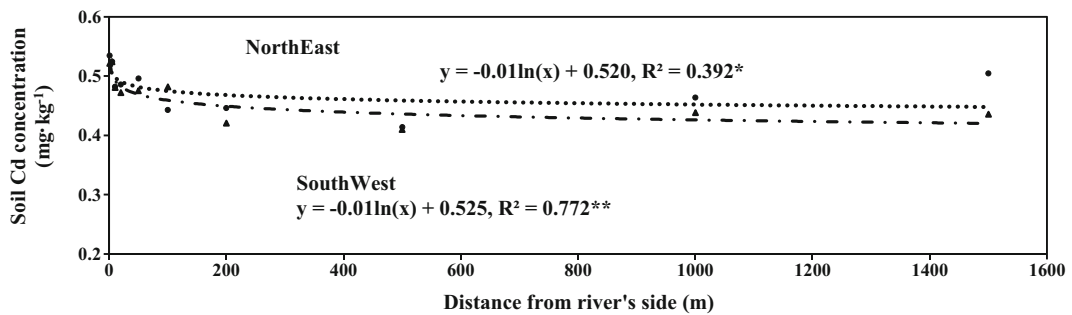


Fig. 7 Horizontal distribution of soil Cd beside the Shiting River. The experimental values (*solid black circle*) and simulation trend (*dotted line*) in northeast and the measured data (*solid black*

triangle) and simulation trend (*dashed line*) in southwest. Differences are significant at $*p < 0.05$ and $**p < 0.01$ of the simulation equation

the Shiting River and Mianyuan River) was extracted to produce a scatter diagram illustrating the relation between soil Cd concentration and distance from rivers (Fig. 6). Soil Cd concentration exhibited a significant ($p < 0.01$) negative relation with distance from the Shiting River, with a coefficient of -0.442 ($n = 149$). Conversely, no significant relation was found between soil Cd concentration and distance from the Mianyuan River (Fig. 6), with a coefficient of only 0.063 ($n = 149$). These results indicated that the Shiting River might have been polluted by Cd from the external environment. The soil Cd concentration was higher closer to the riverbed. The relationship between soil Cd concentration and distance from the Shiting River did not correspond to the generally accepted rule that soil Cd adheres primarily to fine particles away from river beds (Huang et al. 2012; Yuan et al. 2013), likely because the soil around the Shiting River has been polluted by Cd from the external environment. Recent research has shown that the Shiting River contains more Cd (1.19 mg kg^{-1} in water) than the Mianyuan River (0.79 mg kg^{-1}), a finding that

may be attributed to the abundance of chemical plants along the Shiting River. In particular, many phosphorus-manufacturing chemical plants are located in its upper reaches (Wang et al. 2012).

With increasing distance from the bank of Shiting River, the soil Cd concentration first increased and then decreased (Table 7), reaching minimum values of approximately 100–200 m from the river’s bank. This result indicates that the influence of the river on soil Cd concentration can extend to 200 m at most. At greater distances, soil Cd accumulation was likely caused by other factors (e.g., atmospheric pollutant deposition). The relation between soil Cd concentration and distance from the rivers exhibited a logarithmic form (Fig. 7). Because of the coefficient of determination (R^2), soil Cd concentration extending from the southwest bank was more closely correlated with distance from the bank than that in northeast. This result indicated that soil Cd pollution extending from the southwest bank was affected primarily by one single dominant factor, namely, the Shiting River.

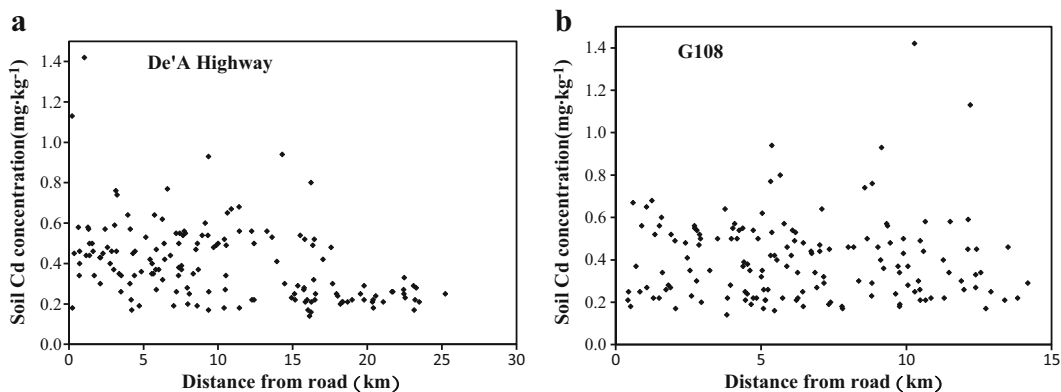


Fig. 8 Scatter plots of soil Cd concentration and distance from the main road. **a** Deyang–Aba (De’A) Highway. **b** National Highway 108# (G108)

Table 8 Soil Cd concentration in roadside areas

Distance from roadside (m)	Deyang-Aba Highway (De'A Road)		National Highway 108 [#] (G108)	
	Road east	Road west	Road east	Road west
1	0.84 ± 0.02a	0.85 ± 0.01a	0.95 ± 0.02a	0.99 ± 0.01a
5	0.84 ± 0.02a	0.83 ± 0.02a	0.93 ± 0.02a	0.90 ± 0.04b
8	0.78 ± 0.03b	0.79 ± 0.02b	0.73 ± 0.02b	0.76 ± 0.02c
10	0.68 ± 0.01c	0.68 ± 0.03c	0.62 ± 0.01cd	0.66 ± 0.04d
20	0.64 ± 0.02d	0.67 ± 0.02cd	0.60 ± 0.02de	0.63 ± 0.01de
50	0.62 ± 0.01d	0.67 ± 0.02c	0.56 ± 0.04ef	0.60 ± 0.03ef
80	0.54 ± 0.04e	0.46 ± 0.01f	0.54 ± 0.04f	0.57 ± 0.03fg
100	0.44 ± 0.01f	0.49 ± 0.03f	0.65 ± 0.02c	0.54 ± 0.03g
200	0.46 ± 0.02f	0.57 ± 0.03e	0.48 ± 0.02g	0.53 ± 0.03g
400	0.64 ± 0.02d	0.63 ± 0.03d	0.53 ± 0.03f	0.48 ± 0.02h

Note: The number of soil samples at different distances was ten. Means with the same letter do not differ significantly at $p < 0.05$ using T-tests

Transportation action

A scatter diagram of soil Cd concentration in farmland and the distance from each sampling point to nearby trunk roads is presented in Fig. 8. The correlation coefficient between distance from the Deyang-Aba Highway and soil Cd concentration was -0.421 ($n = 149$) and was not significant ($p < 0.01$). Conversely, the relation between distance from National Road 108[#] (G108) and soil Cd concentration was significant ($r = -0.02$, $n = 149$). This result may be related to the fact that the Deyang-Aba Highway runs from south to north through the Jingyang District, whereas the G108 Highway runs east to west, spanning the border of the Jingyang District (Wang et al. 2007a; Ouyang et al. 2009). Moreover, dust fall from traffic had little effect on soil Cd accumulation near G108.

The soil Cd concentration in farmland near Deyang-Aba road and G108 was high, particularly within 50 m of the road shoulder (Table 8). The difference of the soil Cd concentrations in farmland near G108 and Deyang-Aba road was possibly due to variables such as transportation time, traffic flow, and the protection zone scope (Wang et al. 2007a; Kar et al. 2010; Heintzman et al. 2015). Wind direction also resulted in different distributions on different sides of these roads. The dominant wind direction in the study area was northeasterly, which likely resulted in the higher concentration of Cd in farmland soils on the west sides of both roads (running approximately north to south) compared to their east sides (Fig. 9).

The results indicated that soil Cd concentration continued to decrease further with increasing horizontal distance from the roads (Fig. 9). Broadly, soil Cd accumulated

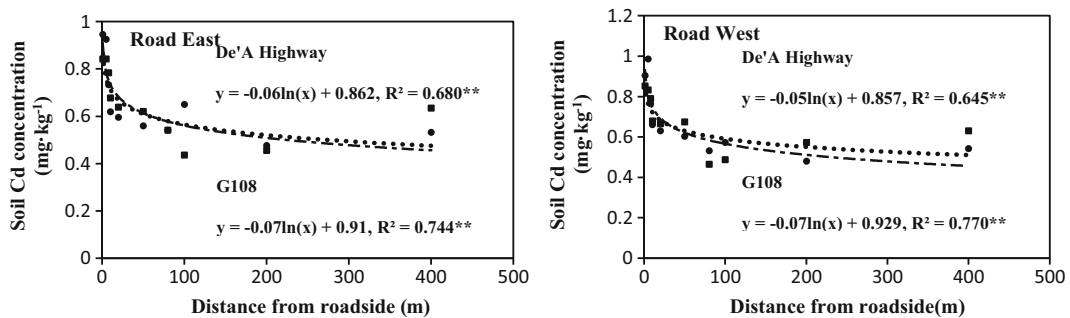


Fig. 9 Horizontal distribution of soil Cd in roadside areas. The experimental values (solid black circle) and simulation trend (dashed line) distance from the roadside of De'A Highway and

the measured data (solid black square) and simulation trend (dashed line) distance from the roadside of G108. Differences are significant at $*p < 0.05$ and $**p < 0.01$ of the simulation equation

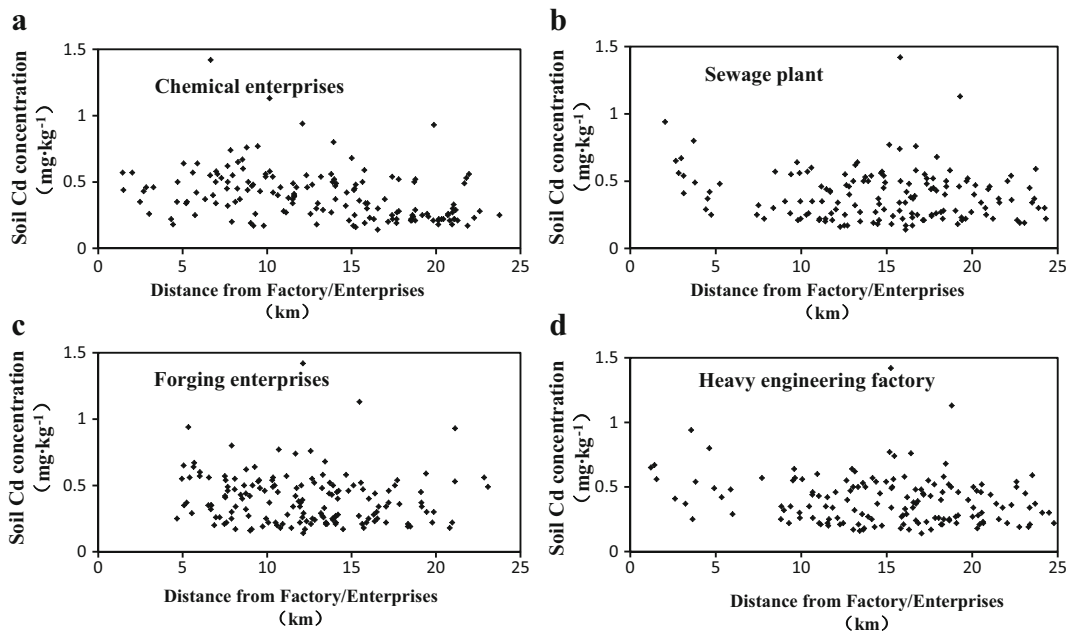


Fig. 10 Plots of soil Cd concentration and distances from main industrial factories/enterprises. **a** Chemical enterprises. **b** Sewage plant. **c** Forging enterprises. **d** Heavy engineering factory

primarily 0–50 m from the shoulders, particularly in the 0–20-m interval. Soil Cd declined considerably at 20–50 m, declined more slowly at 50–100 m, and stabilized at 100–200 m. Accordingly, the soil Cd concentration exhibited almost no change between distances of 200 and 400 m from the roadsides. Considering the regional value of soil Cd ($0.40 \pm 0.19 \text{ mg kg}^{-1}$), the roads appeared to be the primary factors influencing soil Cd pollution risk for locations within 200 m of the roadsides. This conclusion is supported by previous studies that concluded heavy metals in car emissions tended to move vertically over distances of 45–60 m (Yan et al. 2013), whereas other studies have shown that heavy metal pollution influenced by roads and transportation could reach locations 150–350 m from the shoulder, depending on protection zone characteristics, wind velocity, and wind direction (Zhu et al. 2006). Thus,

to mitigate the resulting soil Cd pollution, measures such as building protective forests may prove effective at 0–200 m away from the roadside.

Industrial enterprise emissions

No significant relationship was found between soil Cd concentration and distance to either the heavy machinery enterprises or the sewage treatment plant (Fig. 10). However, a significant negative relation was found between soil Cd concentration and the distance from chemical plants ($r = -0.359$). Previous studies have suggested that the source of emission was also important in such relationships (Wu et al. 2005; Zhou et al. 2006). Therefore, the sampling distance was reduced to analyze the fine-scale influence of the spatial distribution of

Table 9 Regression analysis between soil Cd concentration and influencing factors

Main controlling factors	<i>R</i>	<i>R</i> ²	Adjusted <i>R</i> ²	<i>F</i>	Sig.
Soil parent material	0.397	0.158	0.140	9.042	<0.01
Soil types	0.514	0.264	0.205	4.473	<0.01
Distance from river (Shiting River)	0.491	0.241	0.236	46.779	<0.01
Distance from road (De'A Road)	0.470	0.221	0.215	41.634	<0.01
Distance from chemical factory (Meifeng and Yuanfeng plants)	0.405	0.164	0.158	28.806	<0.01

industrial enterprises on the surrounding soil (Sharma and Tripathi 2008; Yan et al. 2009).

The significance test results for soil Cd concentration near the chemical plants indicated that the soil Cd concentration within 10 m ($0.59\text{--}0.78\text{ mg kg}^{-1}$) was higher than it was within 15–100 m ($0.47\text{--}0.58\text{ mg kg}^{-1}$) or 300–400 m (0.38 mg kg^{-1}). However, no significant difference in the soil Cd concentration was found between 100 and 300 m ($0.46\text{--}0.47\text{ mg kg}^{-1}$). Thus, soil Cd pollution was concentrated primarily within 100 m of chemical plants, although soil Cd decreased slowly in the range of 100–400 m.

A logistic curve can be used to fit the relation between soil Cd concentration (Y , milligrams per kilogram) and the distance to the chemical plant (X , meters) ($n = 20$), as follows: $Y = -0.072\ln(X) + 0.8451$, $R^2 = 0.8288^{**}$. Within 0–50 m of the plant was the primary source of soil Cd pollution. This result agreed with the results of a previous study (Bao et al. 2011). Another study showed that, as the distance from a plant chimney increased, the heavy metal concentration of soil first increased and then decreased slowly, in contrast to the results presented here (Zhang et al. 2009a, b). However, this discrepancy may be attributed to the fact that wastewater was the primary emission from the chemical plant.

Source identification based on main controlling factor analysis

The independent variable (i.e., adjusted R^2) ranked the influencing factors as follows: distance from river (Shiting River) > distance from road (De'A Road) > soil type > distance from chemical factory (Meifeng and Yuanfeng plants) > soil parent material (Table 9). Among them, river migration, soil type, and soil parent material can reflect the natural geological process, and distance from chemical factory and road can reflect human activity factors. Thus, the results indicated that distance from Shiting River and Deyang-Aba Highway accounted for the highest fraction of soil Cd concentration variation. The distance of the Shiting River reflected the succession of the parent material deposition in the study area and the influence of the later soil-forming process. Therefore, the distance of the Shiting River could reveal more geological background information than soil parent material and soil type could. In addition, distance from Deyang-Aba Highway also appeared to be the primary factor influencing soil Cd pollution risk. This finding is supported by previous studies that concluded that heavy metals in car emissions tend to move

vertically (Yan et al. 2013). Therefore, in order to mitigate the resulting soil Cd pollution, measures such as building protective forests may prove effective at 0–200 m away from the roadside. However, the distance from chemical plants (i.e., the Meifeng and Yuanfeng plants) and soil parent material explained the least variance in soil Cd pollution. The chemical plants were not the major source of soil Cd pollution arising from human activity. Similarly, soil parent material exerted only a slight influence on soil Cd pollution, although its influence might be linked to soil type. Therefore, natural geological factors play greater roles than human activity factors in determining the heterogeneity of soil Cd.

Conclusions

The soil Cd concentration in an industry-based peri-urban area of Chengdu Plain (Jingyang District, Deyang City) was higher than the average agricultural soil background value (“old wall soil” from the 1960s to the 1970s, $\text{Cd} = 0.29\text{ mg kg}^{-1}$). Soil Cd pollution was concentrated in the towns of Tianyuan, Bajiaoqing, Bolong, Huangxu, and Xiaoquan. Geoaccumulation caused by human activity exerted little influence, but the potential ecological risk was high. Influencing factors on soil Cd pollution were shown as follows: distance from river (Shiting River) > distance from road (Deyang-Aba Highway) > soil type > distance from chemical plant (Meifeng and Yuanfeng plants) > soil parent material. The significant horizontal distance from the Shiting River was 200 m, and the pollution risk was high within 400 m of Deyang-Aba Highway and within 100 m of chemical plants (Meifeng and Yuanfeng plants). Moreover, measures should be applied in polluted rivers (especially in both sides of Shiting River) and along arterial traffic routes (e.g., the Deyang-Aba Highway) to alleviate farmland soil Cd pollution.

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