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Environmental Pollution Assessment of Heavy Metals in Soils and Crops in Xinping Area of Yunnan Province, China

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Abstract: With the development of the economy and society, the environmental problems caused by heavy metals have always been the focus of attention. Strong concern has been recently shown for the heavy metal pollution of soils in southwestern China. The heavy metals of surface soils in the Xinping area of Yunnan province, China are surveyed along with some crop samples. There are 3312 surface soils and 95 crop samples collected in about 370 square kilometers. Heavy metals including As, Cd, Cr, Hg, and Pb and pH are analyzed. New single and integrated pollution indices of heavy metals for soils (PI and PI_n) and crops (PI^c and $PI_n{}^c$) based on Chinese criteria (GB15618-2018 and GB2762-2022) are described and presented here and used to assess the pollution status of heavy metals. The results indicate that the background level of surface soils is about 62.1%, the screening level is about 33.4%, and the intervention level is about 4.5%, which is mainly a result from Cr and spatially coincides with the peridotite rock, indicating a geogenic pollution source. Most crop samples are not contaminated with heavy metals. Comparing the results of the two integrated pollution indices between soils and crops, two inconsistent assessments are observed. One is that some contaminated crops are growing in unpolluted areas (or Type I) and the other is that some uncontaminated crops are growing in polluted areas (or Type II). This indicates a new challenge between the assessment criteria on soils and crops.

Keywords: heavy metals; surface soil; crops; pollution index; Xinping area

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1. Introduction

Generally, heavy metals refer to metals whose densities are greater than 5 g/cm^3, such as cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pb), iron (Fe), manganese (Mn), and cobalt (Co), while the metalloid arsenic (As) is usually classified as a heavy metal due to similarities in chemical properties and environmental behavior [1–3]. Concerns over heavy metals are due to their high toxicity, long durability, persistent bioavailability, stability, and profusion [4–6]. Heavy metal pollution not only degrades the quality of the soil, crops, atmosphere, and water bodies, but also threatens human health through the food chain [7–9]. Soils are important sinks for heavy metals discharged into the environment [10–12]. Therefore, heavy metal pollution in soils has become a serious issue that has attracted much attention worldwide [13–15].

Since the 1980s, the economy of China has developed rapidly with the acceleration of industrialization and urbanization, while heavy metal pollution in soil has become increasingly concerning due to competing pressures between the population, resources, and environment [16–18]. Due to the high geochemical backgrounds and activities of mining and smelting in southwest China, the study of heavy metals of soils has been a hotspot of environmental evaluation [19,20].

The assessment methods commonly used for heavy metal pollution can be grouped into two types. One is on heavy metals with established criteria such as Cd, Cr, Hg, Pb, and As with the criterion GB15618-2018 for soil of agricultural land in China [21–24]. The other is on heavy metals without specific criteria such as Fe, Mn, and Co in which the evaluation can be conducted through pollution indices such as single indices and integrated indices [25–28].

In this paper, the heavy metals of surface soils in the Xinping area of Yunnan Province, China are first surveyed on a scale of 1:50,000 along with some crop samples. Then, new single and integrated pollution indices are described and proposed to assess the pollution status of soils and crops on Chinese criteria of GB15618-2018 [21] and GB2762-2022 [29], respectively. Finally, the assessment results between soils and crops are compared and discussed.

2. Materials and Methods

2.1. Geological Settings

The study area was located in the Xinping area of Yunnan province, China (Figure 1a), with an area of about 370 km^2 ranging from E 101°29′ to 101°44′ and N 23°39′ to 23°51′ with grid lines at an interval of 3′ (Figure 1b). According to the public network data, the Xinping area is situated in a temperate zone with humid climate, with an average precipitation of about 900 mm and topography characterized by mountains, and the temperature ranges from 1.3 to 32.8 °C with a mean of about 18 °C. The soil type is mainly lateritic red soil, dry red soil, red soil, yellow brown soil, paddy soil, and purple soil, and the land-use type is dominated by forest land and dry land, followed by paddy field and meadow [30]. The main crops include rice, maize, beans, and buckwheat, and the economic crops are composed of walnuts, sugarcane, citrus, tea, and tropical fruits [31].

The strata in the study area belong to Neoproterozoic, Palaeozoic, Devonian, Carboniferous, Permian, Triassic, and Jurassic, of which petrological descriptions are illustrated briefly in Figure 1b as notes [32–34]. Faults are very common in the study area, trending NW-SE and NNW-SSE [35,36]. Three magmatic intrusions, composed of potassium-feldspathic granite, granite, and peridotite, are known in the area with a trend of NNW-SSE, which is almost parallel to the faults [31,37–39].

2.2. Materials

Based on the sampling grids (8 samples each square kilometer) and the land use types, the surface soil samples were collected vertically from top to bottom along the pit wall within a depth of about 0–20 cm, removing the grass roots, gravel, and fertilizer clumps. Each soil sample was composed of 3–5 sub samples near the sampling point with a weight of about 1 kg. A total of 3312 surface soil samples were collected in the study area with an actual average sampling density of 8.95 samples in each square kilometer.

Maize and rice as bulk grain crops and walnut as an economic crop were collected in the study area on harvest season and sunny days, while avoiding special plants with pests and diseases. Each crop sample was collected from multiple points and mixed evenly to form a composite sample with a weight of about 500 g. A total of 95 crop samples were collected in the study area including 40 maize, 40 walnut, and 15 rice samples.

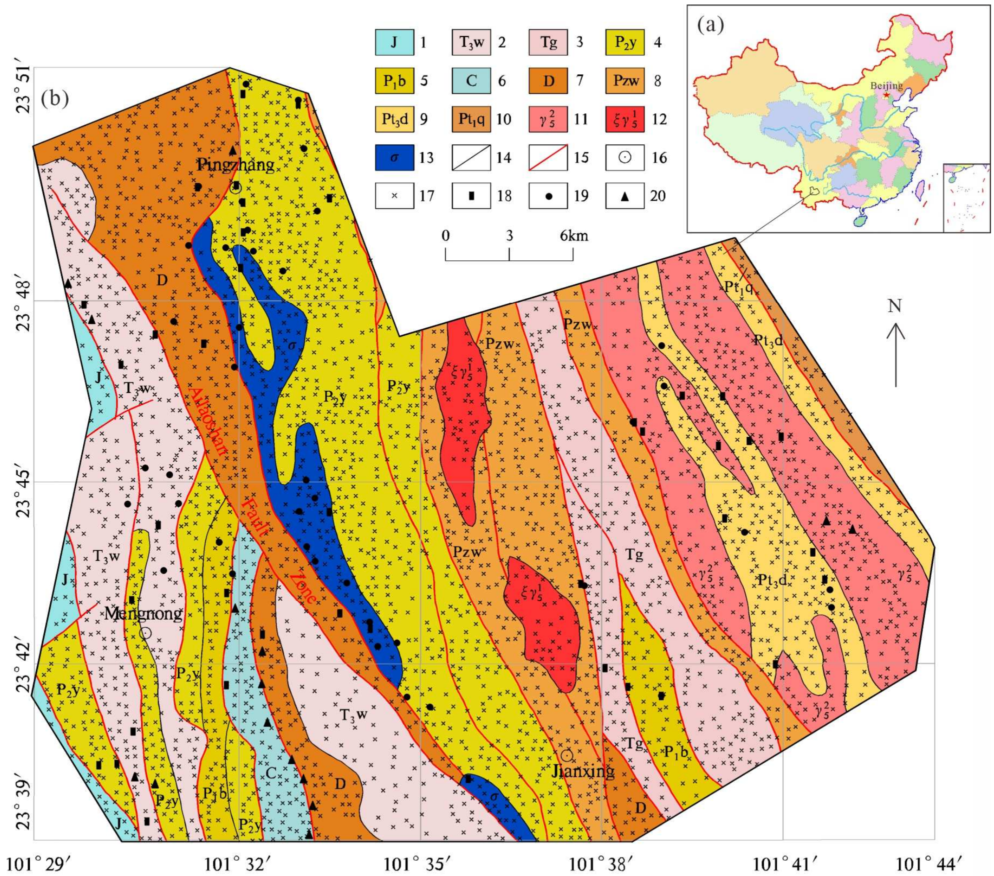

Figure 1. Location of the study area in China (**a**) and its geological map modified after Huang et al. [30] with sample locations of surface soils and crops (**b**). Notes in (**b**): 1—Jurassic sandstone; 2—Upper-Triassic Waigucun Formation sandstone, conglomerate, limestone, and marl; 3—Triassic Ganbatang Formation metamorphic conglomerate, sandstone, and phyllite; 4—Middle-Permian Yangbazhai Formation mudstone, sandstone, and siltstone; 5—Lower-Permian Baliu Formation limestone, siltstone, fine-grained sandstone, mudstone, and siliceous rock; 6—Carboniferous slate, phyllite, fused breccia, and tuff; 7—Devonian sandstone, siltstone, mudstone, limestone, and siliceous rock; 8—Palaeozoic Waimaidi Formation metamorphic sandstone, siltstone, and phyllite; 9—Neoproterozoic Dahebian Formation quartz schist, and phyllite intercalated with leptynite; 10—Paleoproterozoic Qingshuihe Formation of Ailaoshan Group schist, leptynite, and marble; 11—granite; 12—potassium-feldspathic granite; 13—peridotite; 14—petrological boundary; 15—fault; 16—main residential place; 17—locations of surface soil samples; 18—locations of maize samples; 19—locations of walnut samples; and 20—locations of rice samples.

2.3. Analytical Methods

The collected surface soil samples were first naturally air-dried. Then, the soil samples were sieved through a nylon sieve of 10 mesh. Finally, the soil samples were crushed to less than 200 mesh (≤0.074 mm) using a pollution-free planetary ball mill before chemical analysis. The collected crop samples (maize, walnut, and rice) were preprocessed through dehulling or peeling, and rinsed with clean water and then deionized water three times. They were dried naturally and then crushed to pass through nylon sieves of 40–60 mesh in an agate mortar before elemental analysis. And they were digested into sample solution with nitric acid and hydrogen peroxide in a dedicated microwave digester at high temperature and pressure. Then, the contents of heavy metals were determined using an inductively coupled plasma spectrometer, which can scan the plasma with masses ranging between 5 u and 250 u, with the minimum resolution at a peak height of 5% and a peak width of 1 u; and an atomic fluorescence spectrometer, which is equipped with a special mercury lamp.

All chemical analyses were performed at the Center of Laboratory in Yunnan Exploration and Development Bureau of Geology and Mineral Resources (Kunming Testing and Quality Supervision Center for Geological and Mineral Products in the Ministry of Natural Resources, Yunnan Province). The analysis of soil and crop samples was strictly carried out in accordance with the requirements of the Specification of Land Quality Geochemical Assessment (DZ/T 0295-2016) [40]. The data of six items (As, Cd, Cr, Hg, Pb, and pH) were analyzed in this study.

The analytical methods and detection limits of soil samples were as follows. The pH was determined using the ion selective electrode (ISE) with a detection limit of 0.01. The contents of As and Hg were analyzed using the atomic fluorescence spectroscopy (AFS) method with detection limits of 0.05 μg/g and 0.4 ng/g, respectively. Cadmium, Cr, and Pb were determined using inductively coupled plasma–mass spectrometry (ICP-MS) with detection limits of 10 ng/g, 0.82 μg/g, and 0.96 μg/g, respectively. With respect to the crop samples, Cd, As, Cr, and Pb were determined through ICP-MS with detection limits of 10 ng/g, 0.1 μg/g, 0.05 μg/g, and 0.02 μg/g, respectively. Mercury was determined using AFS with a detection limit of 1 ng/g.

The analytical methods, detection limits, accuracy, and precision all met the requirements in Specification of Land Quality Geochemical Assessment (DZ/T 0295-2016) [40]. The analytical qualification rates, controlled by the first-grade standard samples and spiked recovery, were larger than 99.6% for soil samples and 99.4% for crop samples.

3. Results

3.1. Heavy Metal Contents

3.1.1. Soil Samples

The statistical parameters of heavy metal contents and pH in 3312 surface soil samples from the Xinping area are listed in Table 1, and the histograms and their box plots are shown in Figure 2.

Table 1. Statistical parameters of analytical values of surface soil samples in the Xinping area.

Analysis Items	Min.	Q_1	Q_2	Q_3	Max.	n1	Mean1	Mean*	n2	Mean2	Mean**
As	0.05	8.0	15.2	25.4	480	3312	12.9	10.6	3282	13.3	9.1
Cd	10	73	110	180	6130	3312	120	254	3251	116	211
Cr	4.78	79	107	139	4619	3312	112	95	3045	104	87
Hg	8	57	111	179	10200	3312	101	65	3298	100	58
Pb	2.11	25.2	30.9	37.7	855	3312	30.9	41	3190	31.0	36
pH	3.89	4.69	4.93	5.26	8.12	3312	5.02	-	3204	4.96	-

Notes: The units of As, Cr, and Pb are μg/g except Cd and Hg, which are in ng/g. Q_1, Q_2, and Q_3 are first, second, and third quartiles of heavy metal contents and pH values, respectively. Mean1 and Mean2 are the geometric mean contents of surface soil samples from the Xinping area. Mean1 was calculated from all samples, while Mean2 was calculated by repeatedly culling data outliers using the threshold of avg. ±3 SD geometrically. Mean* and Mean** are the geometric mean contents of surface soil (0–20 cm) in Yunnan province after Hou et al. [41]. Mean* was obtained from all samples, while Mean** was calculated by culling data outliers.

The pH values of the surface soil samples vary from 3.89 to 8.12, which can be divided into four parts, $pH \leq 5.5$ for 2803 samples, $5.5 < pH \leq 6.5$ for 418 samples, $6.5 < pH \leq 7.5$ for 82 samples, and $pH > 7.5$ for 9 samples according to the soil criterion (GB15618-2018). The samples with pH values lower than 6.5 are about 97.3%, which indicates that the surface soil in the Xinping area is generally acidic.

Compared to the geometric mean contents of surface soils in Yunnan province [41], it can be seen from Table 1 that the geometric mean contents of As, Cr, and Hg in Xinping area are greater than those in Yunnan Province, while the geometric mean contents of Cd and Pb are lower.

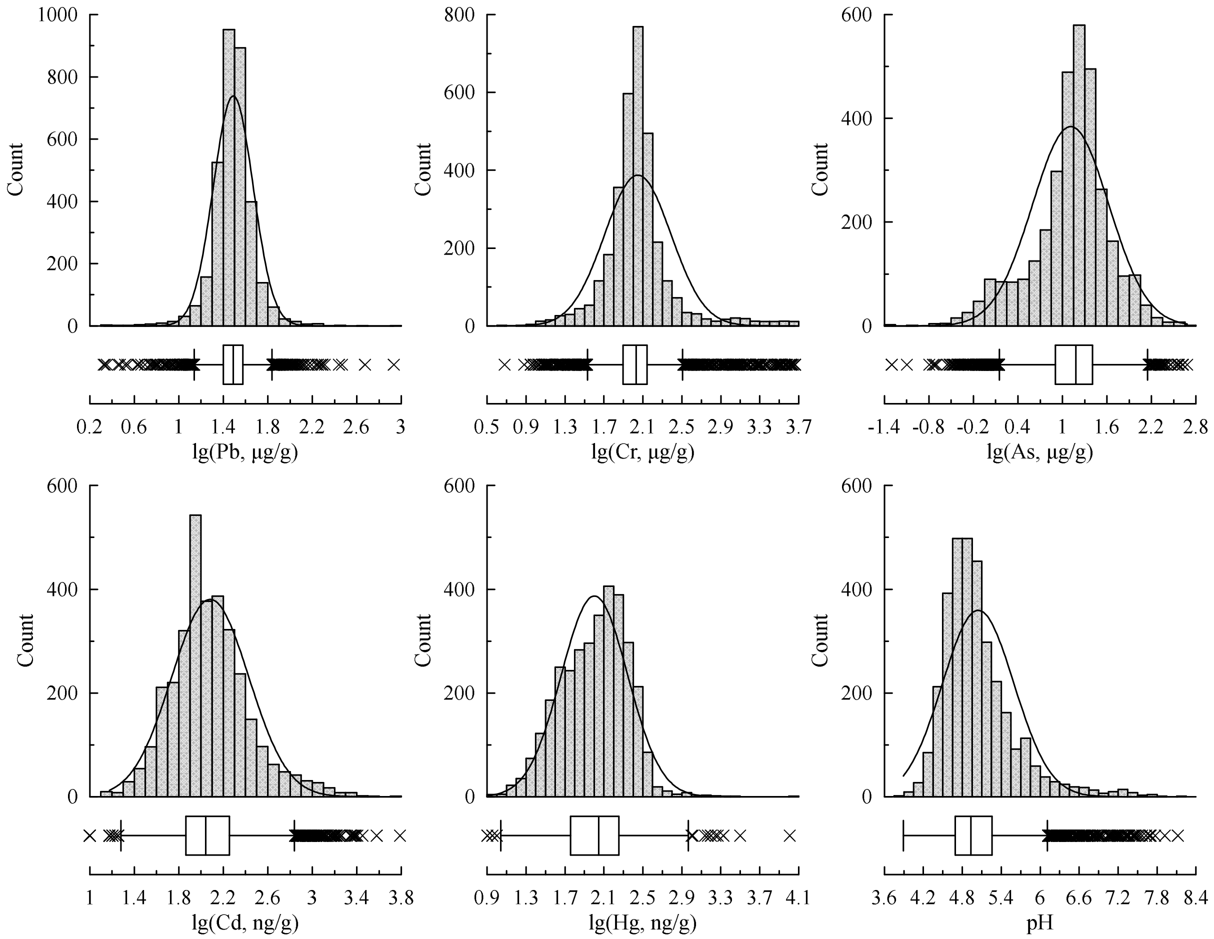

Figure 2. Histograms with box plots of heavy metal contents and pH of surface soil samples from the Xinping area.

3.1.2. Crop Samples

The statistical parameters of heavy metal contents in 95 crop samples from the Xinping area are listed in Table 2.

Table 2. Statistical parameters of analytical values of crop samples in the Xinping area.

Crops Samples	Maize			Walnut			Rice		
Statistical Parameters	Min.	Median	Max.	Min.	Median	Max.	Min.	Median	Max.
As	<0.1	<0.1	<0.1	<0.1	<0.1	0.13	<0.1	0.11	0.20
Cd	<10	<10	26	<10	<10	14.13	<10	33.5	560
Cr	0.10	0.15	0.26	0.51	0.70	0.85	0.24	0.32	1.36
Hg	<1	1.1	1.35	<1	<1	<1	2.7	3.3	4
Pb	0.04	0.07	0.13	0.03	0.08	0.19	0.06	0.09	0.16

Notes: The units of As, Cr, and Pb are μg/g except Cd and Hg, which are in ng/g.

The contents of five heavy metals in maize, walnut, and rice samples are described, respectively, as follows.

Among 40 maize samples, the contents of As are all lower than the detection limit of 0.1 μg/g. The Cd contents in 35 samples are lower than the detection limit of 10 ng/g. The contents of Cr vary between 0.10 and 0.26 μg/g. The Hg contents range from the detection limit of 1 ng/g (in nine samples) to 1.35 ng/g. The contents of Pb vary between 0.04 and 0.13 μg/g.

Among 40 walnut samples, the contents of As in 39 samples are lower than the detection limit of 0.1 µg/g. The contents of Cd range from the detection limit of 10 ng/g (in 38 samples) to 14.13 ng/g. The Cr contents vary between 0.51 and 0.85 µg/g. The contents of Hg are all lower than its detection limit of 1 ng/g. The Pb contents vary between 0.03 and 0.19 µg/g.

Among 15 rice samples, the contents of As range from the detection limit of 0.1 µg/g (in six samples) to 0.20 µg/g. The Cd contents vary from the detection limit of 10 ng/g (in four samples) to 560 ng/g. The contents of Cr range from 0.24 to 1.36 µg/g. The contents of Hg vary between 2.7 and 4 ng/g. The contents of Pb vary from 0.06 to 0.16 µg/g.

3.2. Single Pollution Index

On the basis of the risk screening and intervention values in GB15618-2018, the pollution risk of heavy metal in soil of agricultural land can be divided into three levels and classified as ① the background level, which means that the pollution risk can be ignored if the contents of heavy metals are lower than their risk screening values; ② the screening level, which means the pollution risk is moderate if the contents of heavy metals are equal to or greater than their risk screening values but lower than risk intervention values; ③ the intervention level, which means the pollution risk is high if the contents of heavy metals are equal to or greater than their risk intervention values. Then, the single pollution index of heavy metals for soil of agricultural land was proposed by Huang et al. [42] to qualitatively describe the pollution risk level of heavy metal in soils.

3.2.1. Single Pollution Index for Soils

The single pollution index (*PI*) to describe the contamination risk of heavy metals for soil of agricultural land proposed by Huang et al. [42] is

$$PI = \begin{cases} 0 & C < C_{\mathrm{RS}} \\ 1 & C_{\mathrm{RS}} \le C < C_{\mathrm{RI}} \\ 10 & C_{\mathrm{RI}} \le C \end{cases} \quad (1)$$

where C are the contents of heavy metals in soil samples, and C_{RS} and C_{RI} are their risk screening and intervention values for soil of agricultural land in GB15618-2018, respectively (Table A1).

According to Equation (1), the *PI* values of Hg, Pb, Cd, As, and Cr in 3312 surface soil samples in this study are calculated to draw geochemical maps of the single pollution index of heavy metals in the Xinping area (Figure 3). The geochemical maps of *PI* can not only intuitively visualize the spatial distribution of heavy metal pollution in the area through different color scales [43], but also identify the pollution source for each heavy metal like multivariate statistical analysis and a new geochemical gene technique [44–46].

For Hg, there are 3 samples with *PI* values of 10 that belong to the intervention level, 3 samples with *PI* values of 1 that belong to the screening level, and 3306 samples with *PI* values of 0 that belong to the background level. For Pb, there are 2 samples with *PI* values of 10 that belong to the intervention level, 83 samples with *PI* values of 1 that belong to the screening level, and 3227 samples with *PI* values of 0 that belong to the background level. For Cd, there are 6 samples with *PI* values of 10 that belong to the intervention level, 384 samples with *PI* values of 1 that belong to the screening level, and 2922 samples with *PI* values of 0 that belong to the background level. These results indicate that most areas are classified as the background level except sporadic areas as the screening and intervention level of Hg, Pb, and Cd.

For As, there are 30 samples with *PI* values of 10 that belong to the intervention level, 399 samples with *PI* values of 1 that belong to the screening level, and 2883 samples with *PI* values of 0 that belong to the background level. The result indicates that most areas belong to the background level except small areas belonging to the screening level and sporadic areas belonging to the intervention level.

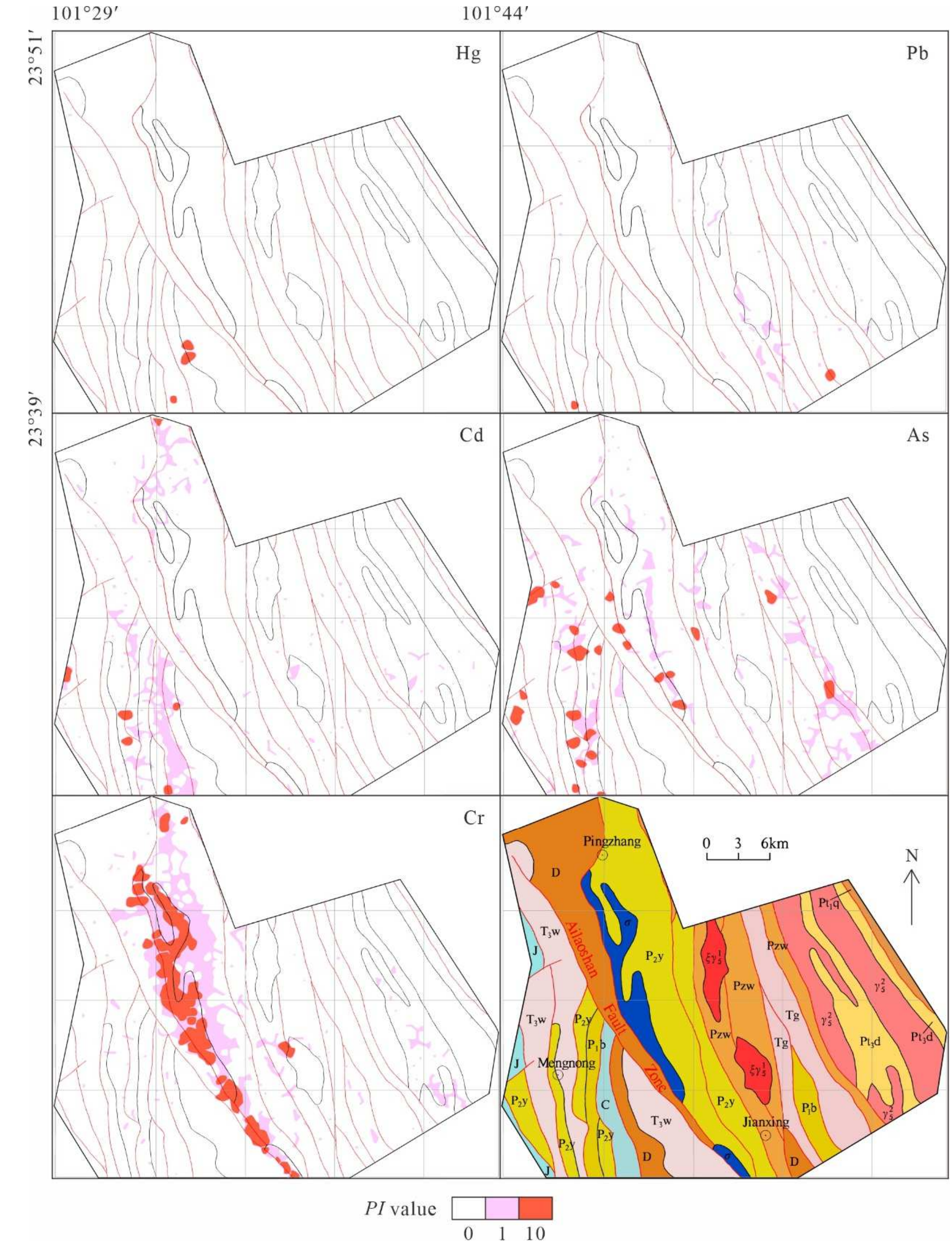

Figure 3. Geochemical maps of the single pollution index of heavy metals in surface soil samples from the Xinping area along with its geological map.

For Cr, there are 112 samples with *PI* values of 10 that belong to the intervention level, 577 samples with *PI* values of 1 that belong to the screening level, and 2623 samples with *PI* values of 0 that belong to the background level. The result indicates that most areas belong to the background level, while some areas belonging to the intervention level are mainly distributed in a planar shape within the area where the peridotite rock is located, and the areas belonging to the screening level are also mainly distributed within the peridotite rock and its surrounding areas in a planar shape. This indicates that the Cr pollution must result from the parent rock.

3.2.2. Single Pollution Index for Crops

Based on the single pollution index (PI) of heavy metal for soil of agricultural land proposed by Huang et al. [42], a single pollution index (PI^c) to describe the contamination degree of crops as food is proposed as

$$PI^c = \begin{cases} 0 \; C < C_{MCC} \\ 1 \; C \geq C_{MCC} \end{cases} \tag{2}$$

where C are the contents of heavy metals in crop samples, and C_{MCC} are their maximum contents of contaminants allowed in food referring to GB2762-2022.

The maximum contents of contaminants allowed in food (Table A2) in GB2762-2022 are adopted in this study. Because the maximum contents allowed in walnut on As, Cr, and Hg are not given in GB2762-2022, the values for As, Cr, and Hg of 0.5 µg/g, 1.0 µg/g, and 20 ng/g, respectively, in grain from GB2762-2022 are used to assess the walnut.

According to Equation (2), the PI^c values of five heavy metals in 95 crop samples from the Xinping area are calculated. For Cd, there are only two samples with PI^c values of 1 that belong to contaminated crops. For Cr, there is only one sample with a PI^c value of 1. For As, Hg, and Pb, all values in 95 samples are 0, indicating unpolluted status.

3.3. Integrated Pollution Index

3.3.1. Integrated Pollution Index for Soils

On the basis of the single pollution index (PI) mentioned above, the integrated pollution index (PI_n) to describe the pollution risk of heavy metals for soil of agricultural land is proposed by Huang et al. [42] as

$$PI_n = \Sigma PI \tag{3}$$

where PI are the single pollution indices of heavy metals mentioned above, and n is the count of heavy metals.

According to Equations (1) and (3), the theoretical values of integrated pollution index (PI_5) for five heavy metals of Hg, Pb, Cd, As, and Cr include 0, 1–5, 10–14, 20–23, 30–32, 40–41, and 50. When PI_5 values are 0, it means that these samples belong to the background level with the contents of the five heavy metals being lower than risk screening values in GB15618-2018. When PI_5 values range from 1 to 5, it means that these samples belong to the screening level with the contents of the five heavy metals being lower than risk intervention values, while there is at least one heavy metal with contents greater than risk screening values. When PI_5 values range from 10 to 50, the tens digit (n) of the PI_5 values indicate the number of heavy metals with contents equal to or greater than risk intervention values.

The actual PI_5 values in 3312 surface soil samples from the study area range from 0 to 21. There are 2057 samples with PI_5 values of 0 belonging to the background level, which is about 62.1% in total; 1107 samples with PI_5 values varying between 1 and 5 belonging to the screening level, which is about 33.4%; 143 samples with PI_5 values ranging from 10 to 14; and 5 samples with PI_5 values varying between 20 and 21, which is about 4.5% in all soil samples. The geochemical map of PI_5 in the Xinping area is shown in Figure 4, which can visualize the spatial distribution of heavy metals to trace integrated anomalies like the mineralization similarity of metallogenes presented recently [47–49].

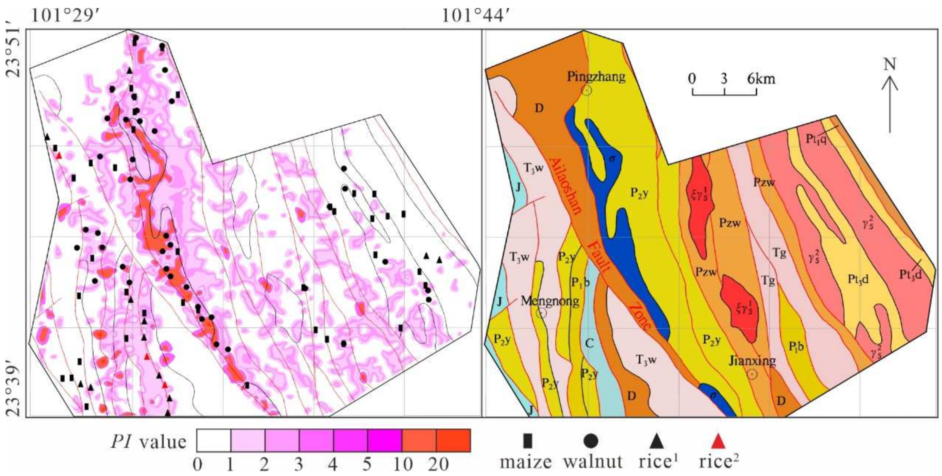

Figure 4. Geochemical map of the PI_5 of heavy metals in surface soils from the Xinping area along with its geological map. Notes: the triangle symbol in black (rice^1) represents the uncontaminated rice samples, while that in red (rice^2) represents contaminated rice samples.

3.3.2. Integrated Pollution Index for Crops

Based on the single pollution index (PI^c), the integrated pollution index ($PI_n{}^c$) to describe the contamination degree of crops as food is proposed as

$$PI_n^c = \Sigma PI^c \quad (4)$$

where PI^c are the single pollution indices for crops as food, and n is the count of heavy metals.

According to Equations (2) and (4), the theoretical values of $PI_5{}^c$ range from 0 to 5. When $PI_5{}^c$ values are 0, it indicates that these samples are uncontaminated crops with the contents of the five heavy metals being lower than the maximum contents of contaminants allowed in food from GB2762-2022. When $PI_5{}^c$ values range from 1 to 5, it indicates that these samples are contaminated crops in which there is at least one heavy metal with contents equal to or greater than the maximum content of contaminants allowed in food.

The actual $PI_5{}^c$ values in the 95 crop samples from the Xinping area range from 0 to 1. There are only three rice samples with $PI_5{}^c$ values of 1.

4. Discussion

In order to test the consistency of pollution status between crops and soils in the Xinping area, 95 crop samples along with 95 corresponding soil samples are abstracted from Figures 3 and 4. Then, the pollution indices of heavy metals between crop and soil samples are compared.

4.1. Between PI in Soil and Contents in Crops

The *PI* values of heavy metals in soils and their contents in crops in the 95 corresponding samples in the Xinping area are illustrated in Figure 5.

For Hg and Pb, all crops are unpolluted and grew in the soils with background-level pollution. For As, Cd, and Cr, most crops are unpolluted and grew in the risk-free-level soils with percentages of about 93.7%, 82.1%, and 77.8%, respectively, in the 95 crop samples. Meanwhile, two polluted crops grew in the screening-level soils (accounting for about 2.1%) for Cd. Therefore, the consistency of pollution status between crops and soils for Hg, Pb, As, Cd, and Cr in the Xinping area are 100%, 100%, 93.7%, 84.2%, and 77.8%, respectively.

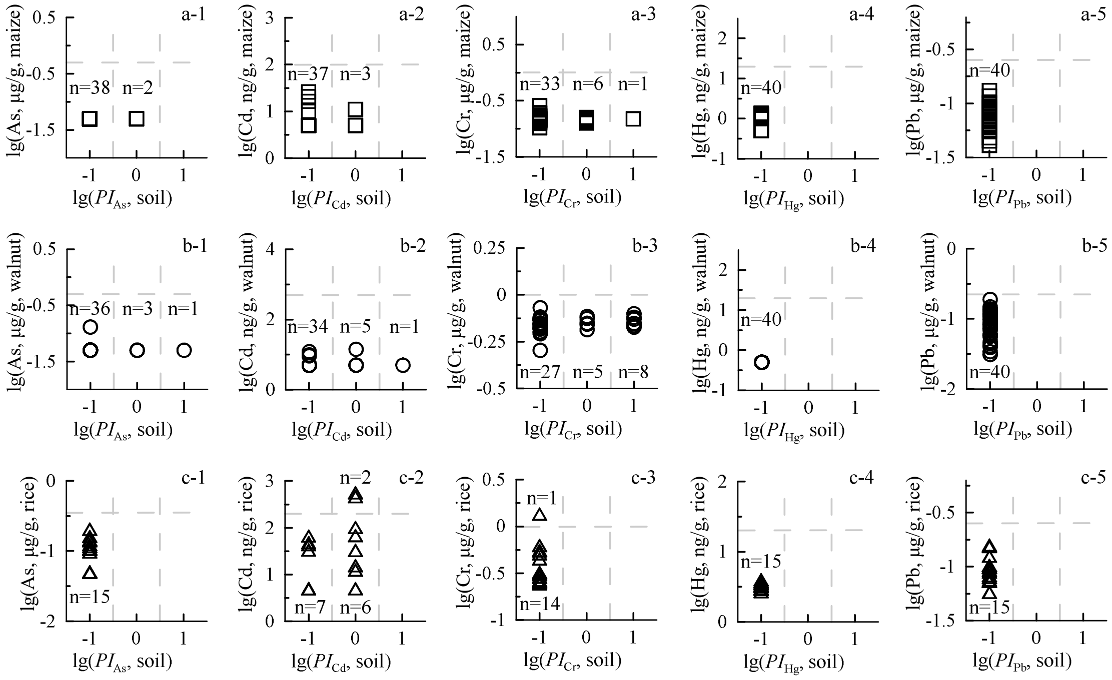

Figure 5. Scatter plots of PI values of heavy metals in soils and their contents in crops in the Xinping area. Notes: (**a-1**–**a-5**) for maize, (**b-1**–**b-5**) for walnut, and (**c-1**–**c-5**) for rice. For a better illustration, the lg(*PI*) is set to −1 when the *PI* values are 0. When the contents of heavy metals are lower than their detection limits, the values of half of the detection limits are used. The values of the dashed lines, perpendicular to the vertical axis, are the logarithmic values of the maximum contents of contaminants allowed in food for heavy metals in GB2762-2022.

However, one polluted crop grew in the background-level soils (accounting for about 1.1%) for Cr. This inconsistency in pollution status between crop and soil is called Type I inconsistency here, while a few unpolluted crops grew in the screening- and intervention-level soils for As (about 5.3% and 1.0%, respectively), Cd (about 14.7% and 1.1%, respectively), and Cr (about 11.6% and 9.5%, respectively). This inconsistency in pollution status between crop and soil is called Type II inconsistency here. These inconsistencies are new challenges between criteria of crops and soils.

4.2. Between PI_5 and PI_5^c

The pollution status of PI_5 and PI_5^c in the Xinping area is illustrated in Table 3 and Figure 6.

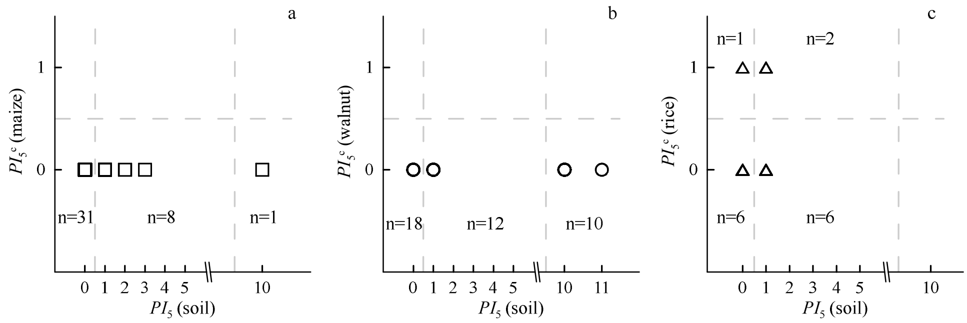

Figure 6. Pollution status between PI_5 and PI_5^c in the Xinping area. Notes: (**a**) for maize, (**b**) for walnut, and (**c**) for rice.

Table 3. The pollution status of PI_5 and $PI_5{}^c$ in the Xinping area.

Crops		Soils		Consistency	
Pollution Status	**n1**	**Pollution Status**	**n2**	**Status**	**Percent**
uncontaminated	92	the background level	55	Yes	59.8
		the screening level	26	Type II	28.3
		the intervention level	11	Type II	11.9
contaminated	3	the background level	1	Type I	33.3
		the screening level	2	Yes	66.7
		the intervention level	-	-	-

Notes: n1 represents the number of crop samples and n2 represents the number of soil samples.

There are 55 corresponding samples with $PI_5{}^c$ = 0 and PI_5 = 0, which means that the uncontaminated crops grew in the background-level soils or the consistency in pollution status. There are two samples with $PI_5{}^c$ = 1 and $1 \leq PI_5 \leq 5$, which also means the consistency in pollution status. Therefore, the consistency percent of pollution status is 60% between crops and soils according to the national criteria in the Xinping area.

There is one sample with $PI_5{}^c$ = 1 and PI_5 = 0, which means that the contaminated crop grew in the background-level soil. This is the type I insistency of pollution status. However, there are 11 samples with $PI_5{}^c$ = 0 and PI_5 = 10 and 26 other samples with $PI_5{}^c$ = 0 and $1 \leq PI_5 \leq 5$. This means the uncontaminated crops grew in the screening-level or intervention-level soils or the type II insistency of pollution status.

Among the aforementioned results on $PI_5{}^c$ and PI_5, two types of inconsistency of pollution status appear according to the criterion GB15618-2018 for soil of agricultural land and criterion GB2762-2022 for food on heavy metal assessments. These inconsistencies are new challenges between the criteria of crops and soils, which needs to be solved urgently in research in the near-future.

5. Conclusions

(1) New single and integrated pollution indices for soils and crops based on Chinese criteria (GB15618-2018 and GB2762-2022) are described and proposed, respectively, to evaluate the degree of heavy metal pollution.

(2) The pollution status of heavy metals in soils and crops in the Xinping area of Yunnan province, China is evaluated using the new pollution indices. The areas polluted by Cr strongly coincide with the peridotite rock in a spatial manner, which indicates a geogenic pollution source.

(3) The results of the pollution indices between crops and their soils show two inconsistent assessments. Some contaminated crops are collected from unpolluted areas and some uncontaminated crops are collected from polluted areas, which indicates a new challenge between the criteria on soils and crops.

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Appendix A

Table A1. The risk control standard of heavy metals for soil contamination of agricultural land extracted from GB15618-2018 of China [21].

Element	Risk Value	pH ≤ 5.5	5.5 < pH ≤ 6.5	6.5 < pH ≤ 7.5	pH > 7.5
Cd	Risk Screening value	300	300	300	600
	Risk Intervention value	1500	2000	3000	4000
Hg	Risk Screening value	1300	1800	2400	3400
	Risk Intervention value	2000	2500	4000	6000
As	Risk Screening value	40	40	30	25
	Risk Intervention value	200	150	120	100
Pb	Risk Screening value	70	90	120	170
	Risk Intervention value	400	500	700	1000
Cr	Risk Screening value	150	150	200	250
	Risk Intervention value	800	850	1000	1300

Notes: The units of As, Pb, and Cr are µg/g except Cd and Hg, which are in ng/g. The type of agricultural land is "others".

Table A2. The maximum contents of heavy metals allowed in food extracted from GB2762-2022 of China [29].

Crops	As	Cd	Cr	Hg	Pb
Maize	0.5	100	1.0	20	0.2
Walnut	0.5 *	500	1.0 *	20 *	0.2
Rice	0.35	200	1.0	20	0.2

Notes: The units of As, Cr, and Pb are µg/g except Cd and Hg, which are in ng/g. *—values in walnut adopted from grain.

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