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Comparison and Analysis of Estimation Methods for Heavy Metal Pollution of Farmland Soils

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Abstract: Heavy metal pollution of farmland soils is a serious environmental problem. The accurate estimation of heavy metal pollution levels of farmland soils is very crucial for sustainable agriculture. Concentrations of heavy metal elements (As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn) in farmland soils at 186 sampling sites in the Baghrash Lake Basin, NW China, were determined and analyzed based on the pollution index (P_i), the geo-accumulation index (I_{geo}), the enrichment factor (*EF*), the ecological risk index (*ER*), and the environmental risk index (I_{er}). The results of these five different estimation methods were compared and discussed. The obtained results indicated that the average concentrations of all the heavy metals in the farmland soils of the study area were lower than the Soil Environmental Quality of China (GB 15168–2018) levels, but the average concentrations of Cd, Cr, Ni, Pb, and Zn exceed the corresponding background values. Significant differences in estimation results existed between the five estimation methods. Based on the identified concentrations, the average P_i, I_{geo}, and *EF* values of the heavy metals in farmland soils decreased in the order of: Zn > Pb > Cd > Cr > Ni > Cu > As, whereas the average *ER* values decreased in the order of: Cd > As > Cu > Pb > Ni > Cr > Zn, and the average I_{er} values decreased in the order of: Cd > Cu > Zn > As = Pb > Cr > Ni. The pollution class values with different estimation methods were ranked as: P_i > I_{geo} = *EF* > *ER* = I_{er}. The obtained results suggest that the most appropriate estimation method and soil background values of farmlands should be used for better understanding the environmental quality of farmland soils. Overall, the *EF* and *ER* methods are recommended for assessing heavy metal pollution risks of farmland soils.

Key words: farmland soil; heavy metal; pollution index; comparison; Baghrash Lake Basin

1 Introduction

Pollution of agricultural soils with heavy metals is a serious environmental problem when it poses a severe threat to human health and the environment (Pan et al., 2016; Wang et al., 2017). Heavy metal element accumulation in agricultural soils can affect the safety of agricultural products and cause potential risks for human beings, animals, plants, and the entire ecosystem (Leake et al., 2009; Guo et al., 2016; Han et al., 2018). According to the "National Survey of Soil Pollution" published by the State Environmental Protection Administration and the Ministry of Land and Resources (MEP, 2014), China faces a significant challenge of environmental deterioration due to heavy metal pollution. About 20×10^6 ha of farmlands in China are polluted by heavy metals (Chen et al., 2015). Pollution of farmlands with heavy metals has threatened the soil environment, food safety, and the sustainable development of agriculture (Lei et al., 2009; Duan et al., 2016; Chen et al., 2018). In light of these issues, research concerning the pollution risk assessment of heavy metals in agricultural soils has emerged as an important frontier in environmental research (Cai et al., 2012; Teresiah et al., 2016; Mamattursun et al., 2018).

Many pollution estimation methods have been applied for

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quantifying the levels of metal pollution in soils (Xie et al., 2010; Hu et al., 2013). The most commonly used pollution assessment methods include the geo-accumulation index (I_{geo}) proposed by Müller (1969), the pollution index (P_i) proposed by Tomlinson et al. (1980), the enrichment factor (*EF*) proposed by Sinex and Helz (1981), the ecological risk index (E_i) proposed by Håkanson (1980), and the environmental risk index (I_{er}) proposed by Rapant and Kordik (2003). Many studies concerning quantitative comparisons of heavy metal pollution of soils have been reported. For example, Wu et al. (2012) reported the pollution level of river sediments by using the geo-accumulation index and ecological risk index, and found that the comprehensive use of different estimation methods can increase the accuracy of assessment results. Shi and Wang (2013) compared and discussed the pollution level of urban street dust by using the pollution index, geo-accumulation index, enrichment factor, and ecological risk index. Their results indicated the importance of unifying the terminologies for pollution classes among the different pollution estimation methods. Zhou et al. (2015) estimated and compared the pollution levels of five metal elements in soil by using the pollution index, geo-accumulation index, enrichment factor, and secondary native ratio method, and found the last method was not suitable for the estimation of heavy metal pollution of soils. Wang et al. (2015) investigated ecological risks of heavy metals in soils surrounding tungsten mines by using pollution index, geo-accumulation index, and ecological risk index, and discussed the advantages and limitations of the related methods. Their results suggested that proper precautions should be taken before choosing an appropriate soil pollution estimation method. Su et al. (2016) used the geo-accumulation index as the pollution index, applied simple mathematical statistics, normal fuzzy numbers, and kernel density estimation to evaluate heavy metal pollution of soil, and made inter-comparisons between the pollution estimation results of these methods. Their results indicated that more complex assessment models will improve the accuracy or comprehensiveness of the pollution assessment results. Xie et al. (2016) discussed the pollution level of soils by using the pollution index, geo-accumulation index, enrichment factor, and ecological risk index, and found that the pollution index method was the optimal method for heavy metal pollution estimation of soils. All of these studies indicate that the accuracy of estimation results of heavy metal pollution levels of soils is very crucial.

Despite its importance for the sustainable development of agriculture, relatively few studies concern the quantitative comparisons of heavy metal pollution of farmland soils. Therefore, in the context of rapid development and strict control policies, it is necessary to compare and discuss the different pollution estimation methods for heavy metal contamination of farmland soils. In this study, farmland soil samples were collected from 186 locations in Baghrash Lake Basin, Xinjiang, NW China, and the concentrations of eight elements in the collected samples were determined. The main goals of this study were: 1) to analyze pollution levels of heavy metals in farmland soils in the study area by using the pollution index, geo-accumulation index, enrichment factor, ecological risk index, and environmental risk index; and 2) to compare and discuss these five different estimation methods for heavy metal pollution of farmland soils. Results from this analysis will provide a scientific basis for the proper estimation of heavy metal pollution of agricultural soils.

2 Materials and methods

2.1 Study area

The research was conducted in a typical inner river basin, Baghrash Lake Basin, which is one of the active areas of agriculture in Xinjiang, NW China (Fig. 1). The basin is situated in the northern part of the Taklimakan desert, at 86°54′–87°29′E and 41°52′–42°22′N, and with an altitude ranging from 1050 m to 1800 m. The climate of the basin belongs to the continental dry type, with an average annual temperature of 8.63 ℃, an average annual precipitation of about 70 mm, and an average annual evaporation capacity of about 2360 mm. The Baghrash Lake Basin is traditionally agricultural area, pepper is the main crop, and the pepper processing industry has become one of the key industries for local farmers to increase their incomes. The main soil types in the study area are desert soils. This area is rich in mineral resources, and dominant minerals include magnesite, iron, coal, marble, limestone sandstone, salt, and mirabilite (Ajigul et al., 2017).

2.2 Sample collection, analysis, and quality control

A total of 195 soil samples (0–20 cm depth) were gathered for the agricultural soils of the Baghrash Lake Basin in May 2016. The sampling points are illustrated in Fig. 1. The sample collection methods adopted in this study were those described in "NY/T 395–2000" (MAPRC, 2000). At each sampling location, five replicate soil samples were gathered, manually mixed on-site, and transferred to the laboratory as one composite agricultural soil sample. In the laboratory, the sampled soil was air dried then ground and sieved through a 0.15 mm nylon mesh. Next, the soil samples were digested as per the procedure detailed in "HJ/T 166–2004" (CEPA, 2004). These digestion solutions were then filtered and diluted to 50 mL by adding deionized water. Finally, the concentration of As was determined using an Atomic Fluorescence Spectrometer (Persee, PF–7, China), while the remaining elements were assessed using a Flame Atomic Absorption Spectrophotometer—Flameless (Agilent 200AA, USA). The detection limits for As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn elements were 0.01 mg kg^{-1}, 0.01 mg kg^{-1}, 0.50 mg kg^{-1}, 0.01 mg kg^{-1}, 0.5 mg kg^{-1}, 0.40 mg kg^{-1}, 0.006 mg kg^{-1}, and 0.5 mg kg^{-1}, respectively.

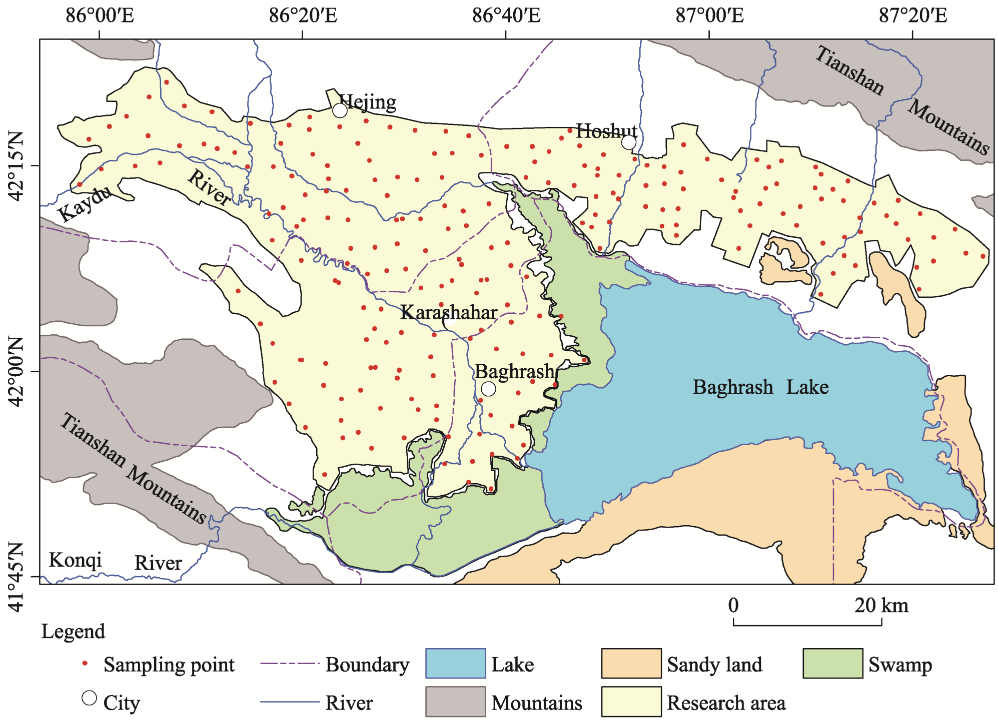

Fig. 1 Map of the location of the Baghrash Lake Basin and the sampling points

The analytical data quality was analyzed using standard laboratory quality control methods, including the use of reagent blanks, duplicates and standard reference materials for each batch of agricultural soil samples. The recoveries from samples that were spiked with standards ranged from 93% to 104%. About 50% of the soil samples were tested repeatedly, and the consistency of the repeated element measurements was about 96%.

2.3 Pollution assessment methods

In this study, the pollution levels of eight heavy metals in farmland soil samples are assessed by five methods, the pollution index (P_i), the geo-accumulation index (I_{geo}), the enrichment factor (EF), the ecological risk index (ER), and the environmental risk index (I_{er}), and the results of these five estimation methods are compared and discussed. The formulas for calculating the P_i, I_{geo}, EF, ER, and I_{er} methods are given in Table 1. The pollution risk degrees of the P_i, I_{geo}, EF, ER, and I_{er} methods are classified as given in Table 2.

Table 1 The calculating formulas for the P_i, I_{geo}, EF, ER, and I_{er} Index

Index	Calculating formula	Characteristics of parameters
P_i	$P_i = C_i/B_i$	Where C_i represents the concentration of element i in the soil sample, and B_i represents the background value of element i
I_{geo}	$I_{geo} = \log_2(C_i/1.5B_i)$	Where C_i and B_i are the same as above, and 1.5 represents a background matrix correction factor that includes possible variations of the background values due to lithogenic effects
EF	$EF = (C_i/C_r)/(B_i/B_r)$	Where C_i and B_i are the same as above, C_r is the concentration of the reference metal, and B_r is the background value of the reference elements
ER	$ER = (C_i/S_i) \times T_i$	Where C_i is the same as above, S_i is the limit-risk concentration of element i, and T_i is the toxic response factor of element i in the soil sample
I_{er}	$I_{er} = (C_i/S_i) - 1$	Where C_i and S_i are the same as above

Table 2 Classification of pollution degrees using P_i, I_{geo}, EF, ER, and I_{er}

Class	P_i	Pollution degree	I_{geo}	Pollution degree	EF	Pollution degree	ER	Risk degree	I_{er}	Risk degree
I	⩽0.7	Unpolluted	⩽0	Unpolluted	⩽2	Unpolluted	⩽40	Low risk	⩽0	Low risk
II	0.7–1	Low	0–1	Unpolluted to moderately	2–5	Low	40–80	Moderate risk	0–1	Moderate risk
III	1–2	Moderately	1–2	Moderately	5–20	Moderately	80–160	Considerable risk	1–3	Considerable risk
IV	2–3	High	2–3	Moderately to strongly	20–40	High	160–320	High risk	3-5	High risk
V	> 3	Extremely	3–4	Strongly	> 40	Extremely	> 320	Extremely high risk	> 5	Extremely high risk
VI	–	–	4–5	Strongly to extremely	–	–	–	–	–	–
VII	–	–	> 5	Extremely	–	–	–	–	–	–

3 Results and analysis

3.1 Concentrations of heavy metals

The minimum, maximum, median, average, and background concentrations of the investigated heavy metals are given in Table 3, along with standard deviation and coefficient of variation values. Note that the background values refer to the element concentrations in agricultural soils in Xinjiang (Zheng, 2007). The "Soil environmental quality—Risk control standard for soil contamination of agricultural land (GB 15618–2018)" values are also given in Table 3. As shown in Table 3, on average, the concentrations of As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn in the collected agricultural soil samples are 6.50 mg kg^{-1}, 0.20 mg kg^{-1}, 55.73 mg kg^{-1}, 30.52 mg kg^{-1}, 503.28 mg kg^{-1}, 34.21 mg kg^{-1}, 41.16 mg kg^{-1}, and 89.31 mg kg^{-1}, respectively. Except for As, Cu, and Mn, all elements present average concentrations that are higher than the corresponding background values. For Cd, Cr, Ni, Pb, and Zn elements, the average concentrations exceed the background values by factors of 1.67, 1.41, 1.30, 3.05, and 5.32 times, respectively. The concentrations of Pb and Zn were significantly higher than their corresponding background values, indicating that Pb and Zn are particularly more abundant in agricultural soils of Baghrash Lake Basin. The average concentrations of all heavy metals in the sampled farmland soils were lower than the levels of Soil Environmental Quality of China (GB 15618–2018). However, the maximum concentrations of As and Zn elements surpassed the recommended values (The Soil Environmental Quality of China (GB 15618–2018)) by factors of 1.15, and 1.45, respectively.

Table 3 Descriptive statistics of heavy metal concentrations in agricultural soil samples (*n*=186)

Items	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Minimum (mg kg^{-1})	0.52	0.05	33.68	19.45	312.82	19.45	0.99	38.99
Maximum (mg kg^{-1})	28.87	0.38	123.39	73.12	789.68	55.97	96.36	434.88
Median (mg kg^{-1})	4.78	0.21	53.80	30.08	501.72	33.96	37.45	73.72
Average (mg kg^{-1})	6.50	0.20	55.73	30.52	503.28	34.21	41.16	89.31
Standard deviation (mg kg^{-1})	4.22	0.06	11.63	6.22	61.76	6.77	24.16	57.80
CV	0.65	0.30	0.21	0.20	0.12	0.20	0.59	0.65
Background value (mg kg^{-1})	11.20	0.12	39.60	35.80	688.00	26.40	13.50	16.80
National Standard (GB 15618–2018) (mg kg^{-1})	25.00	0.60	250.00	100.00	–	190.00	170.00	300.00

The coefficient of variation (CV) shows the degree of variability within the concentrations of each heavy metal element in the soil. A $CV < 0.25$ indicates low variability, while $0.26 < CV < 0.50$ indicates moderate variability, and $0.51 < CV$ is regarded as high variability (Zhang et al., 2015). Heavy metal pollution showing low CV is associated with natural sources, and high CV is typically sourced from human activities. Based on this criterion and the calculated CVs of the analyzed species, the CVs of Cr, Cu, Mn, and Ni in the farmland soils in the study area were all lower than 0.25, indicating low variability for these elements. Cd showed a moderate variability, whereas As, Pb, and Zn each showed a high variability concerning their spatial distributions. This indicates that the concentrations of As, Pb, and Zn vary significantly from one sampling site to the other. Furthermore, the four heavy metal elements belonging to the moderate and high variability groups are those more likely to be affected by extrinsic factors, such as agricultural activities and industry.

3.2 Pollution assessment of heavy metals

The basic statistics of P_i, I_{geo}, EF, E, and I_{er} values for the investigated heavy metals in farmland soils in the study area are given in Table 4.

3.2.1 Pollution index (P_i) of heavy metals

The pollution index (P_i) is used to understand the pollution level of a single heavy metal element in the soil. The background values of heavy metals in the agricultural soils of Xinjiang (Mamattursun et al., 2018) were used in this study. Table 4 summarizes the basic statistics for the P_i of heavy metals in farmland soils in the study area. The P_i ranged from 0.05 to 2.58 for As, 0.42 to 3.17 for Cd, 0.85 to 3.12 for Cr, 0.54 to 2.04 for Cu, 0.74 to 2.12 for Ni, 0.07 to 7.14 for Pb, and 2.32 to 25.89 for Zn. The average values of P_i for As, Cd, Cr, Cu, Ni, Pb, and Zn were 0.54, 1.67, 1.41, 0.85, 1.30, 3.05, and 5.32, respectively. The average values of P_i decreased in the order of: Zn > Pb > Cd > Cr > Ni > Cu > As. Based on the concentrations found and the classification standard, the collected farmland soil samples in the study area were found to be extremely polluted by Pb and Zn, moderately polluted by Cd, Cr, and Ni, have low pollution by Cu, and be unpolluted by As.

3.2.2 Geo-accumulation index (I_{geo}) of heavy metals

The geo-accumulation index (I_{geo}) permits soil heavy metal pollution classification into an appropriate group based on the number of times by which the geochemical background is exceeded. The geo-accumulation index (I_{geo}) values of heavy metals in the farmland soil samples were calculated based on the geochemical background values of agricultural soils in Xinjiang. As shown in Table 4, the I_{geo} values ranged from −5.00 to 0.78 for As, −1.85 to 1.08 for Cd, −0.82 to

Table 4 Statistics of P_i, I_{geo}, EF, ER, and I_{er} values of heavy metals in farmland soils in the study area

Assessment method	Statistics	As	Cd	Cr	Cu	Ni	Pb	Zn
P_i	Minimum	0.05	0.42	0.85	0.54	0.74	0.07	2.32
	Maximum	2.58	3.17	3.12	2.04	2.12	7.14	25.89
	Average	0.54	1.67	1.41	0.85	1.30	3.05	5.32
I_{geo}	Minimum	–5.00	–1.85	–0.82	–1.47	–1.03	–4.35	0.63
	Maximum	0.78	1.08	1.05	0.45	0.50	2.25	4.11
	Average	–1.76	0.07	–0.12	–0.84	–0.24	0.64	1.67
EF	Minimum	0.07	0.64	0.96	0.73	1.00	0.10	3.81
	Maximum	4.16	4.19	3.80	3.10	3.25	11.53	30.75
	Average	0.74	2.30	1.93	1.17	1.78	4.21	7.27
ER	Minimum	0.21	2.50	0.27	0.97	0.51	0.03	0.13
	Maximum	11.55	19.0	0.99	3.66	1.47	2.83	1.45
	Average	2.42	10.04	0.45	1.53	0.90	1.21	0.30
I_{er}	Minimum	–0.98	–0.92	–0.87	–0.81	–0.90	–0.99	–0.87
	Maximum	0.15	–0.37	–0.51	–0.27	–0.71	–0.43	0.45
	Average	–0.76	–0.67	–0.78	–0.69	–0.82	–0.76	–0.70

1.05 for Cr, −1.47 to 0.45 for Cu, −1.03 to 0.50 for Ni, –4.35 to 2.25 for Pb, and 0.63 to 4.11 for Zn. The average I_{geo} values of As, Cd, Cr, Cu, Ni, Pb, and Zn were –1.76, 0.07, –0.12, –0.84, –0.24, 0.64, and 1.67, respectively. The average values of I_{geo} decreased in the order of: Zn > Pb > Cd > Cr > Ni > Cu > As. Clearly, the ranking results of heavy metal pollution calculated by the I_{geo} method are the same as those calculated by the P_i method. Based on the classification standard, the collected farmland soil samples in the study area were found to be moderately polluted by Zn, unpolluted to moderately polluted by Cd and Pb, and unpolluted by As, Cr, Cu, and Ni.

3.2.3 Enrichment factor (*EF*) of heavy metals

The enrichment factor (*EF*) is used to identify enrichment levels and sources of heavy metals in soil (Sutherland, 2000). The reference element is often a conservative one, such as Mn, Fe, Al, etc. (Reimann and Caritat, 2000). Therefore, Mn was chosen as the reference element in the environment studied here, and the *EF* values of As, Cd, Cr, Cu, Ni, Pb and Zn elements were calculated. As shown in Table 4, the *EF* values ranged from 0.07 to 4.16 for As, 0.64 to 4.19 for Cd, 0.96 to 3.80 for Cr, 0.73 to 3.10 for Cu, 1.0 to 3.25 for Ni, 0.10 to 11.53 for Pb, and 3.81 to 30.75 for Zn. The average values of *EF* for As, Cd, Cr, Cu, Ni, Pb, and Zn were 0.74, 2.30, 1.93, 1.17, 1.78, 4.21, and 7.27, respectively. The average values of *EF* decreased in the order of: Zn > Pb > Cd > Cr > Ni > Cu > As, so the ranking results of heavy metal pollution calculated by the *EF* method are the same as those calculated by the P_i and I_{geo} methods. Based on the classification standard of *EF*, the collected farmland soil samples in the study area were found to be moderately polluted by Zn, have low pollution by Cd and Pb, and be unpolluted by As, Cr, Cu, and Ni. Based on the analysis above, the higher P_i, I_{geo}, and *EF* values of Cd, Pb, and Zn indicate considerable Cd, Pb, and Zn pollution of the farmland soils in the study area. This suggests that more attention should be paid to heavy metal contamination of Cd, Pb, and Zn in these soils.

3.2.4 Ecological risk index (*ER*) of heavy metals

The ecological risk index of heavy metals can express the sensitivity of soil ecosystems to toxic substances and can identify the pollution risks caused by heavy metals (Hu et al., 2019). The risk levels of heavy metals in farmland soils in the study area were evaluated using the ecological risk index (*ER*) introduced by Håkanson (1980), and the toxic response factors for As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn were 10, 30, 2, 5, 1, 5, 5 and 1, respectively. In this study, the Soil Environmental Quality of China (GB 15618–2018) was selected for the limit-risk concentration values of the investigated heavy metals. As shown in Table 4, the *ER* values ranged from 0.21 to 11.55 for As, 2.50 to 19.0 for Cd, 0.27 to 0.99 for Cr, 0.97 to 3.66 for Cu, 0.51 to 1.47 for Ni, 0.03 to 2.83 for Pb, and 0.13 to 1.45 for Zn. The average *ER* values for As, Cd, Cr, Cu, Ni, Pb, and Zn were 2.42, 10.04, 0.45, 1.53, 0.90, 1.21, and 0.30, respectively. The average *ER* values of heavy metals decreased in the order of: Cd > As > Cu > Pb > Ni > Cr > Zn, so the ranking results of pollution risks of the elements calculated by the *ER* method are different from those calculated by the P_i, I_{geo}, and *EF* methods. Based on the classification standard of *ER*, the average *ER* values of all heavy metal elements in farmland soils in the study area fell into the low ecological risk level. This indicates that the farmland soil heavy metals analyzed have very low potential ecological risks to soil ecosystems in the study area.

3.2.5 Environmental risk index (I_{er}) of heavy metals

The environmental risk index predicts the probability of negative impacts occurring in the environment via specific pollutants. The I_{er} can be represented by a ratio of analytical to limit-risk concentrations of heavy metals in soil (Rapant and Kordik, 2003). In this study, the Soil Environmental Quality of China (GB 15618–2018) was selected for the limit-risk concentration values of the analyzed heavy metals. As shown in Table 4, the I_{er} values of heavy metals ranged from –0.98 to 0.15 for As, –0.92 to –0.37 for Cd, –0.87 to –0.51 for Cr, –0.81 to –0.27 for Cu, –0.90 to –0.71 for Ni, –0.99 to –0.43 for Pb, and –0.87 to 0.45 for Zn. The average I_{er} values for As, Cd, Cr, Cu, Ni, Pb, and Zn were –0.76, –0.67, –0.78, –0.69, –0.82, –0.76, and –0.70, respectively. The average I_{er} values of heavy metals decreased in the order of: Cd > Cu > Zn > As = Pb > Cr > Ni. The ranking results of environmental risks of elements calculated by the I_{er} method are different from those calculated by the *ER* method. However, based on the classification standard of I_{er}, the average I_{er} values of all analyzed heavy metals fell into the low ecological risk level. This indicates that the farmland soil heavy metals analyzed have very low potential environmental risks to the soil environment in the study area.

4 Discussion

Based on the above analysis, all the pollution classes are calculated and ranked in Table 5. The pollution class values of the farmland soil heavy metals analyzed in the study area can be ranked as: $P_i > I_{geo} = EF > ER = I_{er}$. As shown in Table 5, significant differences in estimation results exist between the five methods. The pollution estimation results of the P_i, I_{geo} and *EF* methods are relatively comparable for each of the estimation data values. The P_i, I_{geo} and *EF* methods all consider the local background values of elements, which makes these three methods have strong comparability in the estimation results. Pollution classes of Cd, Cr, Cu, and Ni range from class Ⅰ to class Ⅲ, while the pollution classes of Pb and Zn range from class Ⅰ to class Ⅴ. The pollution classes obtained using the I_{geo} method are the same as the results obtained with the *EF* method, while the pollution classes obtained using the P_i method are relatively higher than those of the other estimation methods. The P_i method is simple and flexible, and the estimation results of the P_i method can directly reflect the pollution status of soil. However, because it simply regards the pollution levels and element concentrations as a linear relationship, the estimation results are higher than those of other methods. The I_{geo} method improves on the basis of the P_i method, and a logarithmic operation is carried out, resulting in lower estimation results than the P_i method. Compared with the P_i and I_{geo} methods, the *EF* method not only considers the background values of analyzed elements, but also considers the concentration of the reference element. The higher accuracy of the analysis results relative to the reference element can reduce the influences of some inevitable or accidental errors. Therefore, the I_{geo} and *EF* methods are suggested for assessing heavy metal pollution of farmland soils, rather than the P_i method. However, based on the estimation results of the five methods, heavy metals in agricultural soils in the study area, especially Zn, Pb, and Cd, should receive greater attention due to their higher pollution levels and pollution risks.

Table 5 Pollution grades of each element with different assessment methods

Assessing method	As	Cd	Cr	Cu	Ni	Pb	Zn
P_i	I	III	III	II	III	V	V
I_{geo}	I	II	I	I	I	II	III
EF	I	II	I	I	I	II	III
ER	I	I	I	I	I	I	I
I_{er}	I	I	I	I	I	I	I

The pollution classes obtained using the *ER* method are the same as those obtained with the I_{er} method. Pollution risk levels of all the analyzed heavy metals fell into the low risk level according to the classification standards of risk degrees of *ER* and I_{er}. Both the *ER* and I_{er} methods consider the limit-risk value of each element, and the limit-risk values of the analyzed elements are much higher that the local background values of the elements in farmland soils in the study area. Therefore, the pollution estimation results for heavy metals by *ER* and I_{er} are relatively lower than the pollution estimation results of P_i, I_{geo} and *EF*.

The decreasing order of heavy metal pollution levels with different methods is distinctive, as shown in Table 6. With the P_i, I_{geo}, and *EF* methods, the decreasing order of heavy metal pollution levels was totally consistent, with the pollution degree of Zn being the highest, whereas the pollution degree of As was the lowest. The decreasing order of heavy metal pollution levels with the *ER* and I_{er} methods are obviously distinctive compared with those of the P_i, I_{geo}, and *EF* methods. The pollution risk degree of Cd is relatively higher, whereas the pollution risk degrees of Zn and Pb are relatively lower according to the *ER* and I_{er} methods. These differences resulted from the ecological risk factors, which were calculated with the toxic-response factors. The T_i value of Cd is 30, whereas the T_i values of Zn and Pb are only 1 and 5, respectively.

Table 6 Decreasing order of heavy metal pollution

Assessing method	Order
P_i	Zn > Pb > Cd > Cr > Ni > Cu > As
I_{geo}	Zn > Pb > Cd > Cr > Ni > Cu > As
EF	Zn > Pb > Cd > Cr > Ni > Cu > As
ER	Cd > As > Cu > Pb > Ni > Cr > Zn
I_{er}	Cd > Cu > Zn > As = Pb > Cr > Ni

However, the five pollution calculating formulas show that each kind of pollution estimation method takes into account differences in background values. The P_i and I_{geo} methods considered the background value of heavy metals in local agricultural soil, but appropriately determining the background value of heavy metals in a small-scale area is an important scientific problem. The *EF* method highlights the concentration of the reference element in the environment, but choosing the appropriate reference element is very important. Meanwhile, the *ER* and I_{er} methods considered both the toxicity factors and limit-risk values of the heavy metals. Therefore, determination of the toxicity coefficients and limit-risk values of heavy metals in different regions are still problematic. Besides, due to the uncertainty in the terminologies and pollution classes suggested by the five estimation methods, it is difficult to strictly unify the estimation results.

Based on these results, for general pollution level assessment, the P_i method is a simple and quick way to assess the pollution levels of heavy metals in farmland soils. But, the estimation results of the P_i method are quite different from those of the other pollution estimation methods. In the estimation of farmland soil pollution levels, results gained using the I_{geo} and *EF* are relatively close. For pollution risk assessment, the results obtained by the *ER* and I_{er} methods are basically the same, indicating that any of these risk assessment methods can evaluate the pollution risk accurately. But the *ER* method is recommended here because it considers the toxic response factor of heavy metals, which can improve the evaluation accuracy. According to above analysis, the *EF* method is recommended for pollution level estimation, while the *ER* method is recommended for risk level estimation of heavy metals in farmland soils.

5 Conclusions

(1) The average concentrations of eight heavy metal elements (As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn) in farmland soils in the Baghrash Lake Basin, NW China, were 6.50 mg kg^{-1}, 0.20 mg kg^{-1}, 55.73 mg kg^{-1}, 30.52 mg kg^{-1}, 503.28 mg kg^{-1}, 34.21 mg kg^{-1}, 41.16 mg kg^{-1}, and 89.31 mg kg^{-1}, respec tively. The average concentrations of all these heavy metals in farmland soils are lower than the Soil Environmental Quality of China (GB 15618–2018) levels. However, the average concentrations of Cd, Cr, Ni, Pb, and Zn exceed the background values by factors of 1.67, 1.41, 1.30, 3.05, and 5.32, respectively. The higher P_i, I_{geo}, and *EF* values of Cd, Pb, and Zn indicate considerable pollution by them in farmland soils in the study area. Therefore, Zn, Pb, and Cd in farmland soils in the study area should receive greater attention.

(2) Significant differences in estimation results existed between the five methods. The pollution class values with different assessment methods were ranked as: $P_i > I_{geo} = EF > ER = I_{er}$. Based on the identified concentrations, the pollution classes of heavy metals obtained with the I_{geo} method are the same as those obtained with the *EF* method, and the pollution classes obtained using the *ER* method are the same as those obtained with the I_{er} method. Furthermore, the pollution classes obtained using the P_i method is relatively higher than those from the other assessment methods.

(3) The *EF* and *ER* methods are suggested for assessing heavy metal pollution risks of farmland soils. An appropriate pollution estimation method and soil background values should be used for achieving better understanding of the soil environment quality of farmland soils, and it is important to unify the terminologies for the pollution class of different estimation methods in the future.

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农田土壤重金属污染评价方法对比分析

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摘　要：农田土壤重金属污染是突出的环境问题之一。准确评估农田土壤重金属污染水平对农业可持续发展至关重要。从中国新疆博斯腾湖流域采集 186 个农田土壤样品，分析其中 As、Cd、Cr、Cu、Mn、Ni、Pb 和 Zn 等重金属元素含量，采用污染指数法（P_i）、地质累积指数法（I_{geo}）、富集因子法（*EF*）、生态风险指数法（*ER*）和环境风险指数法（I_{er}），分析了农田土壤重金属污染水平，并对 5 种不同评价方法的评价结果进行了比较分析。结果表明，研究区农田土壤中所有元素平均含量均低于国家土壤环境质量标准（GB 15168–2018）的限值，但 Cd、Cr、Ni、Pb 和 Zn 等元素含量平均值超出了相应的背景值。5 种污染评价方法的评价结果之间存在显著差异。大体上，土壤重金属元素的 P_i、I_{geo} 和 *EF* 平均值从大到小依次为：Zn > Pb > Cd > Cr > Ni > Cu > As; *ER* 平均值从大到小依次为：Cd > As > Cu > Pb > Ni > Cr > Zn; I_{er} 平均值从大到小依次为：Cd > Cu > Zn > As = Pb > Cr > Ni。不同污染评价方法得到的污染等级排序为：$P_i > I_{geo} = EF > ER = I_{er}$。为了更好地评估农田土壤环境质量，应采用最合适的污染评价方法和相应的农田土壤背景值。本文建议评价农田土壤重金属污染风险时采用 *EF* 法和 *ER* 法。

关键词：农田土壤；重金属；污染指数；比较；博斯腾湖