Bangladesh J. Bot. **52**(2): 659-669, 2023 (June) Special DOI: https://doi.org/10.3329/bjb.v52i20.68277

ASSESSMENT OF SOIL QUALITY IN HANZHONG CITY BASED ON RISK MANAGEMENT OF HEAVY METAL POLLUTION

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Keywords: Soil fertility, Soil pollution risk control, Classification, Soil quality assessment

Abstract

In the present study, Hanzhong City was taken as an example, and the classification of soil heavy metal pollution risks was performed based on the evaluation of soil fertility status with soil physical and chemical properties as the main indicators. Results showed that the coefficients of variation of soil physical and chemical indicators in the study area were in the descending order: the soil fertility status showed a trend of increasing with decreasing terrain and increasing rivers. The high fertility areas were mainly distributed in the northwest and northeast of the plain area, while the low fertility areas were mainly distributed in the southeastern hilly and mountainous areas and in the western low-lying areas, and the transitional areas surrounded the low-fertility areas. At least 88.89% of the Cd samples and 98.61% of the Cr samples out of the eight heavy metals, Cd, Hg, As, Pb, Cr, Ni, Cu, and Zn, belonged to the priority protection class, while 11.11% of the Cd samples and 1.39% of the Cr samples belonged to the safe use class. The overall distribution of soil quality was similar to that of soil fertility status, while the distribution range of low-quality soil in the southeastern part was smaller and more concentrated. The above research results indicate that the introduction of the classification results of soil pollution risk control types generally reduces the soil fertility status correction and changes the spatial distribution pattern of the original soil fertility status to some extent.

Introduction

Soil is one of the natural environmental elements essential to human survival. In addition to maintaining productivity, it also ensures environmental quality and promotes the health of animals and humans. For a long time, both at home and abroad, the evaluation of soil quality has focused more on the ability of soil to maintain productivity, many researches had been carried out in this regard. Singh *et al.* (2017) used the relative soil quality index (RSQI) to evaluate the changes in the quality of eroded soil caused by 40 years of fertilizer application and continuous cropping of multiple crops. Ma *et al.* (2004) established a comprehensive evaluation index of soil fertility quality by combining the membership degree values of soil fertility evaluation indicators with principal component analysis. Deng *et al.* (2016) evaluated the soil quality index (SQI-MDS) with a minimum data set based on 16 soil physicochemical properties. Liu *et al.* (2017) further calculated the membership degree values of various soil factors based on the premise that each measured value does not have a significant impact on the growth and production of ginseng, and established a soil quality index by combining expert experience method.

However, the increasingly prominent issue of soil environment poses a threat to soil quality, animal, and human health. The traditional soil physical and chemical property indicators are no longer sufficient to meet the requirements for a comprehensive understanding of soil quality. Many scholars have carried out evaluation studies on polluted soil using single-factor pollution

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index method and so on (Zhang *et al.* 2015; Xu *et al.* 2018). Among them, the industrialization and urbanization of industrial cities have become the focus of attention of researchers. For instance, Liu *et al.* (2012) used pollution index and geostatistics to evaluate soil pollution in urban samples of Shanghai. Maierhaimu *et al.* (2017) analyzed the sources of heavy metals in the Weiku oasis based on pollution evaluation. Mazurek *et al.* (2019) extensively used geological accumulation index, pollution factor, toxicity probability, and improved Nemero index to comprehensively evaluate the degree of soil pollution in Ojców National Park .

In recent years, it has become a consensus among some scholars to comprehensively and objectively evaluate and reflect the quality of soil by combining soil environmental quality indicators with traditional soil fertility evaluation systems. Some researchers have made exploratory attempts in this regard. For example, Lu *et al.* (2011) have used a superimposition method to incorporate soil pollution factors into the land grading evaluation system of agricultural land, identifying the dominant pollutants that cause a decrease in the quality of cultivated land in the region. Zheng *et al.* (2018) have taken into account the fact that fertilizers, pesticides, and agricultural films used in cotton fields that have been continuously cultivated for years in Xinjiang can lead to the accumulation of heavy metals in soil (Zheng *et al.* 2018).

Taking Hanzhong City in the southern part of Shaanxi Province, China as study area in the present study eight heavy metal contents in soil and seven physical and chemical indicators were considered. Based on the soil physical and chemical properties, the soil fertility status was evaluated through factor analysis, and the spatial distribution of soil fertility status was studied. At the same time, the agricultural land soil pollution risk control standards were used to divide the study area into different types of soil pollution risk control. On this basis, the results of soil pollution risk control type division are introduced into the soil fertility evaluation system through segmented functions, so as to more accurately reflect the quality of soil and provide scientific basis for monitoring the soil quality of local agricultural land and its safe utilization.

Materials and Methods

The Hanzhong City in the southern part of Shaanxi Province, China are typical areas with fragile soil ecology, so they have been selected as the research area (Fig. 1). The study area belongs to the subtropical monsoon climate with a warm and humid climate throughout the year, and an annual average temperature of 15.7℃. Crops reach maturity twice within a single year. Precipitation is abundant with rainfall throughout the year, and the annual average precipitation is 1177 mm.

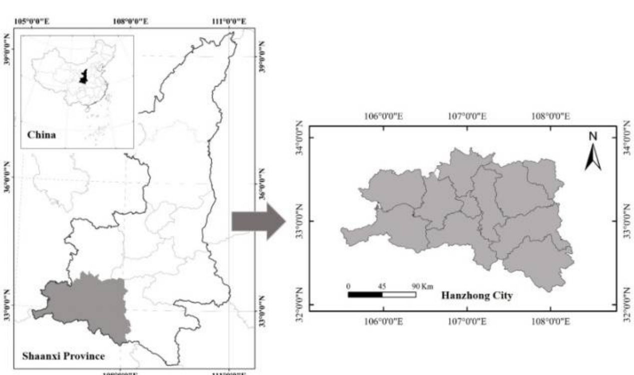

Fig. 1. The location of study area.

In the eastern part of the study area, crop rotation is the main planting method, with rice planted in summer and wheat in winter. Long-acting fertilizers are mainly used for rice in the early stage, while quick-acting fertilizers were used in the later stage, and appropriate external root fertilizers were applied. Wheat mainly uses nitrogen fertilizer, and does not receive organic fertilizer. In the hilly mountainous area of the southern part of the study area, tea is the main crop, and nitrogen, phosphorus, and potassium fertilizers were mainly used. The developed industrial system has caused irreversible damage to the local soil environment. The indiscriminate discharge of solid waste and industrial wastewater has caused serious soil pollution in the surrounding farmland.

Based on the geochemical survey data of the research area at a ratio of 1:10,000 (research area scale), the data points were encrypted and optimized. The investigation results of the research area showed that the degree of heavy metal contamination in agricultural land varied greatly in space, with the most severe pollution in the southeast, slight excess in the northwest, central and southern parts, and less excess in the northeast and western regions. The land use type, soil type, and location factors were also considered when laying out the points to ensure that they were distributed in various pollution levels, towns, and land and soil types. A total of 115 points were laid out throughout the area, with soil sampling depths of 0-20 cm (Fig. 2).

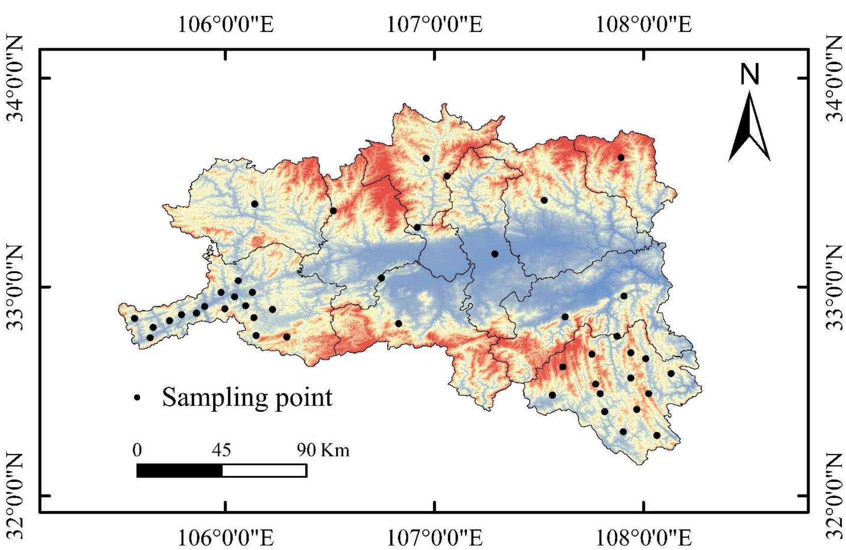

Fig. 2. Distribution of soil sampling sites.

After sampling, quartering method was used to remove excess soil samples, retaining 1 kg of soil sample, which was then stored and transported in a self-sealing polyethylene bag. The collected samples were naturally air-dried and any impurities such as stones were removed. The soil-related indicators were tested by passing the samples through a 100-mesh sieve.

The following methods were used to determine the basic physical and chemical properties of soil: the CEC was measured using the ammonium acetate method (Mattila and Rajala 2021); the TN content was determined using the Kjeldahl method (Yuen and Pollard 2010); the TP content was determined using the NaOH fusion-molybdenum antimony colorimetric method (Baoyong *et al.* 2018); the AP content was determined using the $NaHCO_3$ extraction-molybdenum antimony colorimetric method with a concentration of 0.5 mol/l; the SEC was measured using a DDB-11A portable conductivity meter (soil: water = 1:5); the SOC content was determined using the potassium dichromate volumetric method-external heating method (Jin *et al.* 2021); the pH was determined using the potential method (soil: water = 2.5:1).

The following methods were used to determine the heavy metal contents of the soil. The soil sample was digested with 1:1 aqua regia and As and Hg contents were measured using an atomic fluorescence spectrophotometer; Cd, Pb, Cr, Cu, Ni, and Zn concentrations were measured using ICP-OES. GBW07405 was used as a reference standard in all measurement processes, and the measured values were within the reference range.

Utilizing factor analysis, an evaluation of soil fertility status based on soil physical and chemical properties can be performed. The soil pollution risk screening and control values in the "Control Standard for Soil Environmental Quality of Agricultural Land" issued by the Ministry of Ecology and Environment of the People's Republic of China were used as a reference to classify the types of soil pollution risk control in the study area.

The sampling layout in the research area takes into account the spatial variability of soil and land use types to minimize the impact of their changes on related indicators. However, this leads to uneven distribution of sampling points in different towns. In areas where sampling points are densely distributed, inverse distance weighting may produce a "bull's-eye effect" and affect the accuracy of local interpolation. Ordinary kriging produces smoother interpolation maps, especially in densely sampled areas, and has been found to be superior in interpolation accuracy and error distribution to inverse distance weighting and tension spline interpolation methods. Therefore, the ordinary kriging interpolation method was selected in the present study.

By establishing a piecewise function, the classification of soil pollution risk control results was incorporated into the soil fertility evaluation system. Soil pollution screening and control values divide soil into priority protection, safe use, and strict control categories. The formula for calculating soil quality score is as follows.

$$\begin{cases} F'_F = F_F & X_i \le X_s \\ F'_F = F_F - (F'_{Fmax} - F_{Fmin}) \sum_i^n W_i & X_s < X_i \le X_g \\ F'_F = F_{Fmin} & X_g \le X_i \end{cases} \quad (1)$$

F_F represents the soil fertility status score; F'_{Fmax} represents the maximum value of soil fertility status score; F_{Fmin} represents the minimum value of soil fertility status score; F'_F represents the soil quality score; X_i represents the content of the i-th heavy metal; X_s represents the soil pollution screening value of the i-th heavy metal; X_g represents the soil pollution control value of the i-th heavy metal; F_{Fmin} represents the minimum value of soil fertility status score; and W_i represents the weight of the i-th soil heavy metal content.

The formula for the coefficient of variation of each soil heavy metal content is as follows.

$$V_i = \frac{S_i}{\bar{x}_i} \quad (2)$$

In the formula, V_i represent the coefficient of variation of the i-th heavy metal content in soil, S_i represents the standard deviation of the i-th heavy metal content in soil, and x-bar represents the mean of the i-th heavy metal content in soil.

The formula for the weight of each soil heavy metal content is as follows.

$$W_i = \frac{V_i}{\sum_i^n V_i} \quad (3)$$

Results and Discussion

The coefficient of variation (CV) is an indicator that characterizes the degree of variation of samples, reflecting to some extent the degree to which samples are influenced by human factors. When CV ≤ 0.1, it is considered weak variability; when 0.1 < CV < 1, it is considered moderate variability; when CV ≥ 1, it is considered strong variability. Descriptive statistical analysis of soil physical and chemical properties (Table 1) indicates that the CV of pH is 0.13, indicating weak variability; the CV of TN content is 0.28, CEC is 0.31, SOC content is 0.33, TP content is 0.43, and SEC is 0.93, all indicating moderate variability; the CV of AP content is 1.07, indicating strong variability. Observations show that TN, CEC, SOC, and TP have similar CVS, while pH has the smallest CV and AP has the largest CV, with SEC being in between.

After testing the normality of the original data of soil physical and chemical properties and removing outliers, it was found that TN content, pH, CEC, and SOC content follow a normal distribution, while the other three properties do not. To eliminate the differences in scale and dimension among variables, the standardized data were further processed and tested by KMO and Bartlett's tests. The KMO value was found to be 0.572 (>0.5) and the Sig. value of Bartlett's test was less than 0.05, indicating the structural validity of the data for factor analysis. The resulting eigenvalues and contribution rates are shown in Table 2.

Table 1. Descriptive statistical analysis of soil physicochemical properties.

Value type	CEC/ (cmol/kg)	TN content/ (g/kg)	TP content/ (g/kg)	AP content/ (mg/kg)	SEC content/ (g/kg)	SOC content/ (g/kg)	pH
Minimum	2.4	0.005	0.003	4.2	7.6	3.07	4.2
Maximum	11.5	0.024	0.016	165	438.2	21.5	7.9
Average	7.21	0.014	0.006	28.19	95.54	12.28	6.1
S.E.	2.27	0.004	0.003	30.16	89.13	4	0.79
Coefficient of variation	0.31	0.28	0.43	1.07	0.93	0.33	0.13
Positive distribution or not	Positive distribu-tion	Positive distribution	Logarithmic distribution	Logarithmic distribution	Logarithmic distribution	Positive distribution	Positive distribution

Table 2. Eigenvalue and variance contribution rates of factor analysis.

Common factor	Characteristic value	Variance contribution rate/%	Cumulative contribution rate of variance/%
1(F1)	2.687	38.381	38.381
2(F2)	1.959	27.988	66.369
3(F3)	1.282	18.317	84.686
4(F4)	0.514	7.341	92.027

Upon analyzing the four factors selected in this study, the loadings matrix after factor rotation indicates that the first common factor has a significant loading on the AP, TP content, and SEC indicators, which is related to the spatial dependence of these three soil indicators within a certain range (Table 3). The second common factor has a larger loading on the TN and SOC content indicators, while the third common factor has the largest loading on pH. Lastly, the fourth common factor has the largest loading on CEC.

According to the regression estimation method, the factor score coefficients are shown in Table 4. The functional expression of the factor scores is:

$$F_1 = -0.044X_1 + 0.010X_2 + 0.449X_3 + 0.489X_4 + 0.204X_5 - 0.163X_6 - 0.040X_7 \quad (4)$$

$$F_2 = -0.121X_1 + 0.532X_2 + 0.073X_3 - 0.112X_4 + 0.034X_5 - 0.029X_6 - 0.491X_7 \quad (5)$$

$$F_3 = -0.272X_1 + 0.117X_2 - 0.117X_3 + 0.179X_4 + 0.388X_5 + 0.910X_6 - 0.047X_7 \quad (6)$$

$$F_4 = 1.144X_1 - 0.203X_2 - 0.029X_3 - 0.006X_4 - 0.077X_5 - 0.260X_6 - 0.007X_7 \quad (7)$$

In equations (4) to (6), F_1 to F_4 represent the scores of common factors 1 to 4, while X_1 to X_7 represent the indicators of soil properties, including AP content, TP content, SEC, TN content, SOC content, pH, and CEC. The variable F_F represents the score of soil fertility status.

Table 3. Rotated component matrix.

Soil physical and chemical indicators	Loads for each factor			
	1	2	3	4
AP content	0.956	-0.155	0.027	0.008
TP content	0.920	0.195	0.072	0.072
SEC	0.093	0.067	0.567	0.214
TN content	-0.043	0.971	0.041	0.051
SOC content	0.052	0.959	-0.079	0.142
PH	0.052	-0.060	0.941	0.203
CEC	0.100	0.162	0.262	0.945

Table 4. Scores of component matrix.

Soil physical and chemical indicators	Score coefficient of each factor			
	1	2	3	4
CEC	-0.044	-0.121	-0.272	1.144
TN content	0.010	0.532	0.117	-0.203
TP content	0.449	0.073	-0.117	-0.029
AP content	0.489	-0.112	-0.179	-0.006
SEC	0.204	0.034	0.388	-0.077
PH	-0.163	0.029	0.910	-0.260
SOC	-0.040	0.491	-0.047	0.007

Using the factor score function, the soil fertility scores are calculated based on the weighted sum of the factor scores, with the eigenvalue contribution rate as the weighting factor. The formula for the soil fertility score is: $F_F = F_1 \times 38.381\% + F_2 \times 27.988\% + F_3 \times 18.317\% + F_4 \times 7.341\%$.

In order to further analyze the spatial distribution pattern of soil fertility in the study area, the soil fertility status score was spatially interpolated using ArcGIS software. The specific interpolation results are presented in Fig. 3.

Upon examining the interpolation map, it was observed that the soil fertility is generally lower in the western low-lying areas and the southeastern hilly mountainous areas, while it is generally higher in the northwestern and northeastern parts of the plain. The central region is a boundary zone for soil fertility, exhibiting a good degree of continuity in a strip-like pattern. In the northern plain area, as the number of rivers gradually increases from the central to eastern regions, soil fertility tends to increase as well.

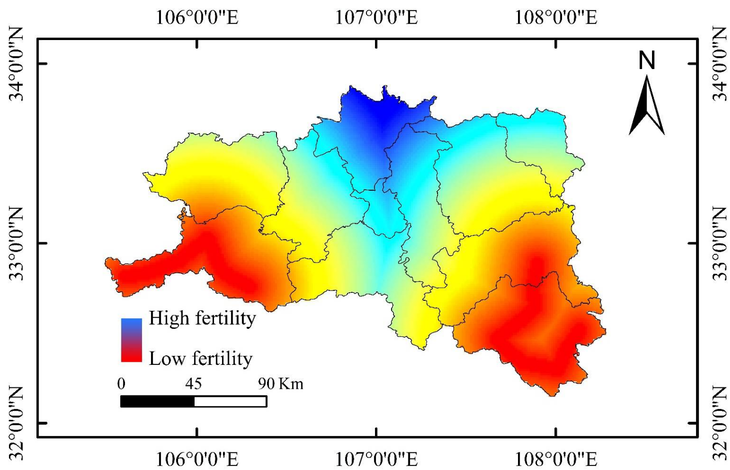

Fig. 3. Spatial distribution of soil fertility.

The analytical results of eight soil heavy metal content indicators including Cd, Hg, As, Pb, Cr, Ni, Cu, and Zn are shown in Table 5. Based on the standard for dividing the types of soil pollution risk control, agricultural land safety utilization is divided into three types (Table 6). This survey shows that there are no sample points in this category within the research area. The specific results of spatial interpolation are shown in Fig. 4. The priority protection category is mainly distributed in the north, east, and south of the research area, surrounding the distribution of the safe utilization category, with good continuity. The safe utilization area is mainly distributed in the southwest of the research area, with sporadic distribution in the northwest, and mainly presents a strip and patch distribution.

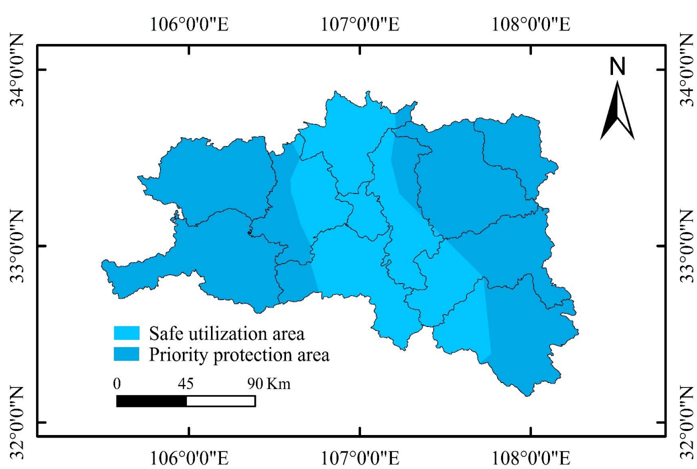

Fig. 4. Classification of soil pollution risk management and control types.

Table 5. Sample point contrast statistics.

Elements	w_B/(mg/kg)		
	Minimum	Maximum	Average
Cd	0.095	0.452	0.242
Hg	0.023	0.312	0.146
As	3.040	16.750	8.611
Pb	21.000	45.267	32.029
Cr	36.333	182.000	78.501
Ni	12.700	73.367	33.032
Cu	12.433	36.867	24.170
Zn	35.167	152.667	68.655

Table 6. Classification of the soil pollution risk control types for agricultural land.

Types	Percentage of sample points in each type							
	Cd	Hg	As	Pb	Cr	Ni	Cu	Zn
Priority protection/%	88.89	100	100	98.61	100	100	100	100
Security utilization/%	11.11	0	0	0	1.39	0	0	0
Strict control/%	0	0	0	0	0	0	0	0

Using the segmented function method, the results of the soil fertility evaluation and soil pollution risk control type classification were combined organically. By applying formulas (1) to (3), 12.50% of the sample points were adjusted to calculate the soil quality in the study area, which is spatially distributed as shown in Fig. 5.

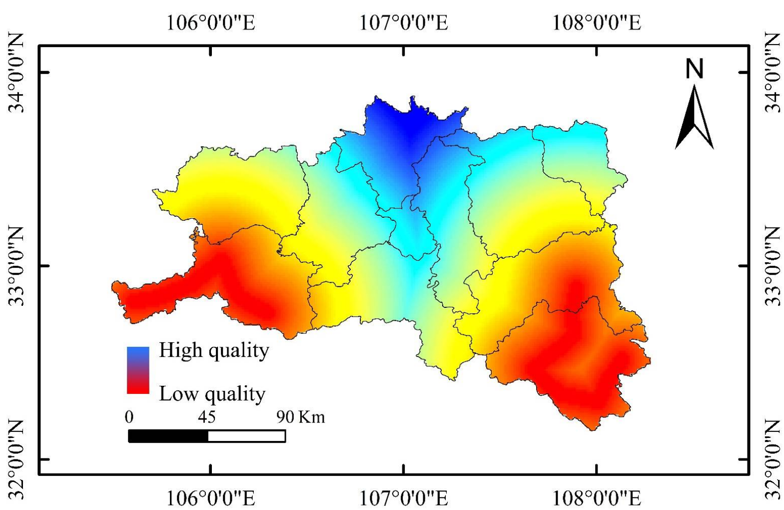

Fig. 5. Spatial distribution of soil quality.

The descriptive analysis of soil physicochemical properties (Table 1) reveals that, except for the AP content, all other soil physicochemical indicators exhibit moderate variability. The pH, which is close to weak variability, may be attributed to its sensitivity to precipitation, and the distribution of precipitation in the study area is relatively even. The TN content, as the primary factor influencing soil fertility, has a low variability coefficient of only 0.28 due to the similar fertilization practices in the densely sampled agricultural land. The TP content, SOC content, and CEC variability are similar because they represent soil fertility from different perspectives. Natural factors such as spatial distribution can have a significant impact on some soil physicochemical indicators, and the SEC exhibited almost strong variability, which may be attributed to the sampling of some points in the collapse zone, where soil moisture conditions differ due to significant fluctuations in water levels (Phillips and Greenway 1998). The AP content has the highest variability coefficient, and the original data shows that the distribution of summer rice sampling points is mainly concentrated in the east of the study area, with typical spatial differentiation (Baldwin and Mitchell 2000). During the rice planting process, the soil is under reducing conditions due to flooding, and soil Eh, pH, and amorphous iron will affect the phosphorus content, increasing its effectiveness and solubility (Gale *et al.* 1994). In addition, prolonged and intense anaerobic conditions caused by flooding convert Fe^{3+} ions to Fe^{2+} ions, which coupled with phosphorus to produce soluble ferrous phosphate that is released into the water, resulting in a decrease in AP content (Watts 2000). Therefore, the variability of AP content is the highest in the entire study area, and it is the most affected by human factors.

The soil fertility in the study area presents a tendency of decreasing with the decline of landforms and increasing with the improvement of quality, which is similar to the results of previous research on the rise of soil fertility after slope improvement (Xue *et al.* 2011). High fertility areas are mainly distributed in the northwest and northeast plain areas, while low fertility areas are mainly distributed in the southeast hilly mountainous areas and the western low-lying areas. This may be due to the fact that the agricultural land in the study area is mainly concentrated in the east, and frequent fertilization may have increased soil fertility. The terrain of the study area is high in the south and low in the north, with an increasing number of rivers from south to north, and soil fertility increases with the increase of rivers, this might be due to the fact that proper irrigation and drainage can significantly improve soil fertility, which is consistent with previous research (Qing *et al.* 2010).

The "safety utilization" category is mainly distributed in the hilly areas of the southwest, while the priority protection category is dominant in the southeastern hilly areas. Investigations have revealed that there are far more industrial and mining enterprises in the southwest of the study area than in the southeast. This indicates that the level of heavy metal content in the soil is not only influenced by factors such as terrain and parent rock, but also closely related to human factors such as land use patterns, which is consistent with the conclusions drawn by previous researchers (Wang *et al.* 2013). Industrial land in the study area is mainly concentrated in the central and southern parts, and the irrigation of industrial wastewater, infiltration of solid waste, and use of chemical fertilizers and pesticides can all lead to an increase in heavy metal content in the soil (Zhang *et al.* 2017).

The selection method for evaluation indicators mainly employs the Minimum Data Set (MDS) and the Total Data Set (TDS) methods (Li and Wu 2018). The advantage of the TDS method is that it utilizes all indicators for evaluation without any selection process. However, applying the TDS method directly to heavy metal pollution evaluation lacks scientific weighting methods and is often independent of soil fertility evaluation based on physical and chemical indicators in past studies.

This study takes Hanzhong City in the southern part of Shaanxi Province, China as study area and completes the investigation of soil physicochemical indicators and heavy metal content. The spatial distribution of soil fertility status was studied, and the soil pollution risk control standards for agricultural land were used to classify the soil pollution risk control types in the study area. It may be concluded that (i) The trend of increasing quality takes place with decreasing elevation and increasing number of rivers. High fertility areas are mainly distributed in the northwestern and northeastern plains, while low fertility areas are mainly found in the southeastern hilly and mountainous areas and the western low-lying areas; (ii) the safe utilization areas are mainly distributed in the southwestern part of the study area, while the priority protection areas surround the safe utilization areas. (iii) the distribution pattern of soil quality is similar to that of soil fertility, but the range of low-quality soil in the southwest of the study area is expanding to the east, while the range of low-quality soil in the southeast of the study area is shrinking and becoming more densely distributed.

This study provides a new idea for the combination of soil fertility and soil pollution risk control type classification results in the future, which is of great practical significance for a more comprehensive understanding of the spatial distribution characteristics of soil quality and a more reasonable use and supervision of agricultural land.

Acknowledgments

The present work was funded by Provincial State-Owned Capital Operation Budget Science and Technology Innovation Special Fund Project "High Standard Farmland Management and Digital Key Technology Research of Modern Agriculture Demonstration Zone", Key R&D Project of Shaanxi Province (No. 2022FP-34), Inner scientific research project of Shaanxi Land Engineering Construction Group (DJNY-ZD-2023-1, DJTD-2023-1, DJNY-YB-2023-18, DJNY-YB-2023-28, DJNY2022-32).

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(Manuscript received on 23 March, 2023; revised on 10 August, 2023)