Nature Environment and Pollution Technology
An International Quarterly Scientific Journal | ISSN: 0972-6268 | Vol. 15 | No. 3 | pp. 915-922 | 2016

Original Research Paper

Spatial Distribution and Economic Loss Estimation of Heavy Metals in the Soil of Northern Areas of Shanxi Province, China

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 15-05-2016
Accepted: 18-06-2016

Key Words:
Heavy metals in soil
Spatial distribution
Economic losses

ABSTRACT

This study analyses the spatial autocorrelation of heavy metals in the soil of northern areas of Shanxi Province, China, and quantitatively calculates the economic losses caused by heavy metal pollution in soil. This study is based on 96 sample data obtained from 32 districts and counties in the northern areas of Shanxi Province, China. This study first adopts three kinds of spatial weight matrixes (i.e., rook, queen, and k-nearest) to estimate Moran's I index, which is an indicator of the content of heavy metals in soil. Moreover, this study assesses the distribution and spatial autocorrelation of heavy metals in the soil of northern areas of Shanxi Province, China. Then, economic loss model of heavy metal pollution in soil is determined based on the pollution loss rate method. The pollution loss rate of four common heavy metals in soil (Cd, As, Cu, Cr) and the total economic losses caused by pollution are quantitatively calculated. Results indicate that content indicators of Cd, As and Cu in the northern areas of Shanxi Province are positive. The three heavy metals in soil generally have positive spatial correlation, and Moran's I index of Cr has negative value under the effect of the three weight matrixes. Hence, negative spatial correlation is determined in terms of spatial distribution. The single heavy metal pollution loss rate is between 1.11% and 1.39%, and the overall difference is small. The comprehensive heavy metal pollution loss rate is 5.24%, which fall undergrade in terms of contamination grade division. Although this result still belongs to clean level, the economic loss of heavy metal pollution in soil is large, which is around 63.765 million yuan (RMB). The conclusions of this study can provide theoretical basis and decision-making references to relevant government departments and industrial enterprises on the prevention of heavy metal pollution and environmental governance.

INTRODUCTION

Soil is an important part of ecosystems on earth. The content of the biochemical substance in soil affects the growth of plants on the soil surface, especially when the contents of various chemical substances exceed the standards. Although these substances may not affect the normal growth of plants, chemical substances can enter the human body and accumulate in the body of other animals through food chain, and ultimately affect human health. Industrial development and urbanization have accelerated the accumulation of heavy metals in soil, caused heavy metal pollution in soil, and expanded the polluted areas yearly. In China, agricultural soil suffers from heavy metal pollution and the enrichment of heavy metals in farmland reduces crop yield and quality to a certain extent, as well as a serious threat to ecosystem and human life.

Heavy metal refers to metals with proportions of more than or equal to 5.0, such as Cd, Cr, Cu, Hg, Ni, Pb and Zn. Generally, heavy metal pollution in soil means that intensive amounts of heavy metals reintroduced into the soil through human activities. This situation leads to that the contents of heavy metals in soil becoming significantly higher than the background value of the soil. Moreover, the high content can degrade existing or potential soil quality, thereby resulting in ecological and environmental deterioration. The accelerated urbanization and rapid development of industries have made the migration of heavy metals into the biosphere arising from human activities an important process of heavy metal environment biogeochemical cycling. Improvement of urbanization level and expansion of city size promote regional industrial development and increase population. However, improper land use, emissions of "three wastes," and significant increase in the application amounts of pesticides and fertilizers easily lead to accumulation of heavy metals in soil. The northern areas of Shanxi Province consist of Xinzhou, Shuozhou, and Datong, and have harsh environment, poor infrastructure, backward social and economic development, and serious environmental pollution. The region has arid windy climate, widely distributed decertified land, as well as bare ground surfaces and many coal yards in the mining area. These factors exert significant impact on air pollution and the environment. Therefore, large quantities of pollutants in the soil may weaken the ecological functions of soil and the environment, as well as pose threats to the health of humans, animals, and plants. Therefore, research on the distribution and economic losses of heavy metal pollution in the soil of northern areas of Shanxi

Province is theoretically and practically valuable in regulating the relationship between economic development and protection of cultivated land.

EARLIER STUDIES

After conventional pollutants have attracted public attention, toxic substances in the environment, especially heavy metal pollution, have become a controversial research topic in recent years. The spatial distribution of heavy metals and economic losses caused by heavy metal pollution can be studied from two aspects. The first comprises influencing factors and actual spatial distribution of heavy metals in soil, and the second is the problem of environmental economics, which is the extent of economic losses caused by heavy metal pollution. The influencing factors and actual spatial distribution of heavy metals in soil have been studied. Thornton investigated the local water environment in Swansea, a southern port city of Wales and the metal smelting industrial centre in the world; the author found serious pollution of heavy metals, such as Cu, Zn, and Pb, in the studied area (Thornton et al. 2001). Rybicka found that large amounts of waste generated by mining and smelting industries in Poland cause serious air, soil, surface water, and groundwater pollution; the author proposed that heavy metal pollution and chloride contamination must be given attention (Rybicka 1996). Jaradat defined heavy metal pollution as the pollution caused by heavy metals with significant biological toxicity, such as Hg, Cd, Cr, and metalloid As; the author also claimed that these heavy metals can pollute the soil for a long time and cannot be easily removed (Jaradat et al. 2005). Chen studied the role of different types of soil contamination on rice; the author found that continuous enrichment of heavy metals in soil significantly affects plants and human health (Chen et al. 1991). Nicholson found that the heavy metals in agricultural soil, such as Zn, Cu, and Cd, mainly come from atmospheric deposition, sewage sludge, livestock manure, pesticides, irrigation water, and three industrial wastes; the author also calculated the change range of the total input of each source (Nicholson et al. 2003).

Murray studied heavy metals in the soil of the Michigan watershed; the author concluded that the content of Pb, Hg, Ni, Zn, and other heavy metals gradually decrease with soil depth and distance from urban and industrial centres (Murray et al. 2004). Ersoy used statistical methods to conduct spatial analysis of heavy metals in the soil of a farmland in Britain, and recommended ways to control heavy metal pollution risks and repair the polluted soil in the area (Ersoy et al. 2004). Sabyet studied the spatial distribution and content of Pb in the soil near Paris, France, and estimated the relationship between Pb content in the surface soil and human activities (Saby et al. 2006). Martín performed multivariate statistical analysis on the contents of seven kinds of heavy metals on the topsoil of a farmland in Ebro Basin, Spain; the author argued that spatial variability of heavy metals is caused mainly by human factors (Martínet al. 2006).

Economic loss caused by heavy metal pollution in soil is a popular research topic in the field of environmental economic losses. In recent years, several studies have focused on environmental economic method and evaluation models of heavy metals in soil. Darilek argued that, given the rapid increase in large-scale cultivation facilities, rural regions of China have significantly increased their investment in the amount of fertilizers and agrochemicals, and increased land use intensity (Darilek et al. 2009).Yu considered the characteristics of soil pollution, adopted pollution loss rate method to evaluate the soil environmental quality of a vegetable suburb of Fuzhou City, and found that the application of pollution loss rate method in soil environment pollution loss analysis is scientific and reasonable (Yu et al. 2008). Shao studied Zhangjiagang City in the Yangtze River Delta as an example; the author used different evaluation criteria and methods to evaluate the pollution status of the Cd, Hg, Pb, Cu, As, and Cr in soil, and discussed similarities and differences of evaluation results derived from different evaluation criteria and methods (Shao et al. 2008). Xu applied pollution loss rate method to conduct soil environmental quality evaluation in the sewage irrigation region of Huafei River, Kaifeng City; the results indicated that the single pollution loss rate of Cd and As of most soil samples is significantly higher than that of other heavy metals (Xu et al. 2009). In conclusion, domestic and international studies have consistently shown that heavy metals in soil come mainly from human factors, are closely related with transportation and industrial production, and have certain correlation with spatial distribution. Economic losses caused by heavy metals in soil are objective facts. The total amount of economic losses differs from region to region, and related with industrial development and governance level.

This study explores the current situation of heavy metal pollution in the soil of the northern areas of Shanxi Province. Quantitative methods are used to determine the spatial distribution of the four common soil pollutants in the region, estimate economic losses caused by heavy metal pollution in soil, and provide basis for coordinating the relationship between economic development and environmental protection in the study area.

MODEL AND DATA SOURCES

Analysis of Spatial Autocorrelation

The analysis of spatial autocorrelation tests whether the attribute value of certain variable in a particular spatial position is significantly correlated with the attribute value of a neighbouring spatial position. Spatial autocorrelation can be divided into global and local spatial autocorrelation. The former tests whether the attribute value of the variable has relevance and regularity in space, while the latter reflects the aggregation or discrete region of the attribute value of variables in space. Moran's I statistic is the most commonly used spatial autocorrelation index, and space weight matrix is an important item that determines the spatial position of the attribute value of the variable. Spatial weight matrixes generally selected by researchers themselves, and may have spatial weight based on adjacency relation or distance.

The space weight matrix based on distance standard is adopted to calculate the Moran's I of discrete point. If the distance between two points is less than the specified threshold value, then the two points are considered adjacent and the weight is1; otherwise, the weight is 0. Global Moran's I index mainly determines the correlation of the attribute value of a variable in spatial position, and then determines whether the regionalized variable has spatial clustering and isolation space in the research area. Therefore, this study adopts Moran's I coefficient to achieve endogenous regional grouping. The definition is shown as follows:

$$Moran's\quad I=\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(Y_i-\bar{Y})(Y_j-\bar{Y})}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}} \qquad ...(1)$$

Where $S^2=\frac{1}{n}\sum_{i=1}^{n}(Y_i-\bar{Y})^2$, $\bar{Y}=\frac{1}{n}\sum_{i=1}^{n}Y_i$, i represents observed value of the Y_i th city (in this paper,theamount of urban haze), n is the total number of cities, and W_{ij} is the binary weight matrix of adjacentspace.

Space weight matrix W is defined as

$$W_{ij}=\begin{cases}1; & when\ area\ i\ is\ adjacent\ with\ j\\ 0; & when\ area\ i\ is\ not\ adjacent\ with\ j\end{cases} \qquad ...(2)$$

Where $i=1,2,\cdots,n$; $j=1,2,\cdots,m$; $m=n\ or\ m\neq n$

Pollution Economic Loss Model

Heavy metal pollution loss rate: Assuming that n kinds of heavy metals are present in soil, and R_j is the heavy metal pollution loss rate of the j heavy metal on soil. To calculate heavy metal pollution loss rate, R_j the differential equation between heavy metal concentration and economic losses of soil environment needs to be established, and is shown as Formula (3).

$$\frac{dS}{dc_j}=\beta_j\frac{S}{K}(K-S) \qquad ...(3)$$

Where c_j is the mass concentration of heavy metal j in the soil (unit: mg/kg); S is the amount of economic losses caused by heavy metal pollution in soil when mass concentration of heavy metal j is c_j (unit:10,000 yuan); K is the economic value after soil utilization (unit: 10,000 yuan); and β_j is the scale factor of heavy metal j in soil. According to Formula (3), the following formula can be obtained:

$$S(c)=\frac{K}{1+\alpha_j\exp(-\beta_j c_j)} \qquad ...(4)$$

Formula (4) complies with a logistic equation, and is the pollution economic loss model of heavy metal j, α_j is the constant term derived from the solution process, which is a simplified model. If

$$R_j=\frac{1}{1+\alpha_j\exp(-\beta_j c_j)} \qquad ...(5)$$

Then $S = KR_j$, where R_j is the loss rate of heavy metal j on soil environment. This relationship is called single heavy metal pollution loss rate.

Determining parameters: In Formulas (4) and (5), α_j and β_j are the constant terms of Formula (2) derived from the solution process ($\alpha_j > 0$). These terms are related to the polluting characteristics of heavy metals, and generally need to be determined by heavy metal toxicological test or actual investigation on polluted environmental resources. The damages of heavy metal on soil are reflected as the impaction corresponding plants and plant-eating animals. This approach is more reasonable, but involves complicated issues because no complete set of information exists at present. In this study, half of the first standards in Heavy Metal Quality Standards of Chinese Soil Environment (GB 15618-1995) (representing the natural background values) is set as the reference to determine parameters α_j and β_j (Liu et al. 1997). These parameters are presented in Table 1.

The specific method is as follows. The background concentration of the j heavy metal in the environment is set as c_{oj}; the corresponding single heavy metal pollution loss rate is R_{oj}; the critical concentration that causes severe pollution is c_{tj}; and the corresponding single heavy metal pollution loss rate is R_{tj}, which is substituted into Formula (5). The following binary equation is obtained:

$$\begin{cases}R_{oj}=\dfrac{1}{1+\alpha_j\exp(-\beta_j c_{oj})}\\ R_{tj}=\dfrac{1}{1+\alpha_j\exp(-\beta_j c_{tj})}\end{cases} \qquad ...(6)$$

To facilitate expression, the definition is as follows:

$$f_j = \ln\frac{R_{tj}(1-R_{oj})}{R_{oj}(1-R_{tj})} \qquad ...(7)$$

According to Formulas (6) and (7), the following equation is obtained:

$$a_j = \left[(1-R_{oj})/R_{oj}\right]\exp\left[f_j c_{oj}/(c_{tj}-c_{oj})\right] \text{ or}$$

$$a_j = \left[(1-R_{tj})/R_{tj}\right]\exp\left[f_j c_{tj}/(c_{tj}-c_{oj})\right],\ \beta_j = f_j/(c_{tj}-c_{oj}) \qquad ...(8)$$

Loss function of soil pollution caused by various heavy metals: When a variety of heavy metals act on the soil environment and resources, the combined effect of various heavy metals is not the sum of the effect of all the heavy metals. The economic loss model of heavy metal pollution in soil considers heavy metals as an organic whole and uses set and probability theories to derive comprehensive heavy metal pollution loss rate. For example, if two heavy metals *A* and *B* are in the soil, then the corresponding single heavy metal pollution loss rates are R_A and R_B, respectively. The probability of the sum of *A* and *B* equals the sum of the two events' probabilities subtracting the product of the two events' probabilities, that is $R_{AB} = R_A + R_B - R_A * R_B$. Hence, the comprehensive heavy metal pollution loss rate of n kinds of heavy metals is

$$R = 1-\prod_{j=1}^{n}(1-R_j) \qquad ...(9)$$

However, different heavy metals account for different weights, and have different contribution rates to the comprehensive heavy metal pollution loss rate. Therefore, Formula (9) is improved by considering that different heavy metals account for different weights. The weight of each heavy metal is determined by the principal component analysis method in multivariate statistical analysis (Sun et al. 1995). The specific steps of the method are as follows. First, the eigen value and contribution rate of the key component of each heavy metal factor are calculated. The contribution rates of previous two main factors (70.82%) must meet the requirements for extracting information. Second, the corresponding load matrix and common factor variance of each heavy metal recalculated. The size of variance represents the contribution rate to comprehensive variation. Finally, the weight of each heavy metal is calculated by the variance value, which is as follows:

$$R = 1-\prod_{j=1}^{n}(1-R_j\omega_j n) \qquad ...(10)$$

Where ω_j is the weight occupied by the *j* heavy metal; *n* is the species of heavy metals in soil.

The economic loss caused by the pollution of single heavy metal *j* is

$$S = KR \qquad ...(11)$$

Where *R* is represented by Formula (10).

Data Source and Processing Instructions

The northern areas of Shanxi Province consist of 32 districts including 14 districts of Xinzhou City, 9 districts of Shuozhou City, and 9 districts of Datong City. A total of 3 sampling points are selected in each district and thus 96 samples are collected. Each sampling point accounts for 6-8 topsoil samples (at depth of 0-20 cm). The soil is mixed evenly and packed in 1-kg to 2-kg bags. After drying the soil samples in the laboratory, stones, roots, and other impurities are removed. The soil samples are then ground with agate mortar to the size of 0.149 mm for analysis. As determined by aqua regia digestion-atomic fluorescence spectrometry, Cd, Cr, Cu, and other heavy metals are decomposed by four acids, HCl-HF-HNO3-HClO4. Cd is determined by graphite

Table 1: Soil heavy metal pollution grade (*mg/kg*).

Heavy metal	GradeI (clean)	GradeII (relative clean)	GradeIII (slight pollution)	GradeIV (moderate pollution)	Grade V (severe pollution)
Cd	0.12	0.25	0.6	1.4	2
As	10	17	30	50	70
Cr	74.88	99.54	150	350	500
Cu	28.37	40.63	120	280	400

Table 2 Moran's I index of heavy metals in soil under different spatial weight matrixes.

Type of heavy metal	*Cd*	*As*	*Cr*	*Cu*
Rook	0.312	0.026	-0.642	0.265
Queen	0.367	0.019	-0.035	0.196
K-nearest	0.269	0.174	-0.265	0.397

furnace-atomic absorption spectrometry (GF-AAS). Cr and Cu are determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES). To ensure reliability and accuracy of the analysis results, each batch of samples (nearly 40 samples) and each project must have two standard samples and two parallel blanks, and 10%-20% of parallel samples must be obtained.

EMPIRICAL RESEARCH

Spatial distribution of heavy metals in the soil of northern areas of Shanxi Province, China: The 96 soil samples collected from the northern areas of Shanxi Province are tested and analyzed. The contents of the four kinds of heavy metals in the soil are measured. Geoda software is used to analyse Moran's I index of the contents of heavy metals in soil rook, queen, and k-nearest spatial weight matrixes. The results are shown in Table 2.

Table 2 shows that, under the rook, queen, and k-nearest weight matrixes, Moran's I index values of Cd, As and Cu are larger than zero. This result indicates that the Cd, As and Cu contents have positive spatial correlation in the northern areas of Shanxi Province. Spatial clustering area is indicated and the Moran's I index values of Cd and Cu and are large, indicating large spatial correlation degree. The Moran's I index of As is small, and its spatial relevance is small. The Moran's I index of Cr is less than zero, indicating that Cr has negative spatial correlation and an isolation area is present. The Moran's I index of Cr has large absolute value and spatial correlation degree is relatively large.

After considering the impact of rook, queen, and k-nearest weight matrixes, Cd, As, and Cu and content indexes show positive values. Hence, the three heavy metals in soil generally have positive spatial correlation. However, the Moran's I index of Cr is negative under the action of the three weight matrixes, that is, this metal has negative correlation in terms of spatial distribution.

Losses caused by heavy metal pollution in the soil of northern areas of Shanxi Province: Taking the soil baseline value of northern areas of Shanxi Province as background concentration, the assumption is that the single heavy metal pollution loss rates of the j heavy metal are1% and 99%, respectively, under the condition of background concentration status and critical state of severe pollution. The values of α and β are calculated according to Formula (8), and are presented in Table 3.

According to the classification criteria of heavy metal pollution in soil in Table 1 and parameters α and β in Table 3, the range of comprehensive heavy metal pollution loss rate with different grades of heavy metal pollution is calculated. The results are given in Table 4.

The heavy metal pollution loss rate of each item, comprehensive heavy metal pollution loss rate, and total amount of economic losses are calculated according to Formulas (5) and (10), as given in Table 5.

As shown in Table 4, the order of individual heavy metal pollution loss rate is as follows Cr>As>Cu>Cd. The corresponding weights are $\omega(Cr)=0.25$, $\omega(As)=0.22$, $\omega(Cu)=0.23$, and $\omega(Cd)=0.3$. The individual heavy metal pollution loss rate is within the range of 1.11%-1.39%, and the overall difference is small. The comprehensive heavy metal pollution loss rate is 5.24%. According to the classification criteria in Table 4, the pollution is Grade II, with relative clean level. The amount of economic losses caused by heavy metal pollution is large, which is approximately 63.765 million yuan (RMB).

POLICY RECOMMENDATIONS

Reasonably adjusting economic restructure and upgrading the industrial structure: According to the actual situation of the three cities in the northern areas of Shanxi Province, China should vigorously conduct the following tasks: promote the transformation from labour-intensive industrial structure into economic technology-oriented industrial structure with high added values; exploit the advantages of economic and technological development zones, high-tech industrial development zones, and tourism development areas; actively introduce and cultivate high-tech industries; promote clean production; actively develop new eco-friendly pillar industries, such as automobile, bio-pharmaceuticals, optoelectronics, and deep processing of agricultural and related products; and promote sustainable economic development of northern Shanxi.

Meanwhile, China should differentially treat the old pollution sources in urban centres, highlight key principles, and

Table 3: Parameters of economic loss model of heavy metal pollution in soil.

Parameter heavy metal	*Cd*	*As*	*Cr*	*Cu*
α	271	364	301	264
β	5.094	0.156	0.026	0.021

Table 4: Classification criteria of soil heavy metal pollution loss rate.

Comprehensive heavy metal pollution loss rate/%	Grade
<4.489	Grade I (clean)
4.489-8.610	Grade II (relative clean)
8.610-35.868	Grade III (slight pollution)
35.868-99.770	Grade IV (moderate pollution)
99.770-99.999	Grade V (severe pollution)

Table 5: Soil heavy metal pollution loss rate and the amount of economic losses caused by pollution.

	Cd	*As*	*Cr*	*Cu*	Comprehensive
Heavy metal pollution loss rate/%	1.11	1.22	1.39	1.14	5.24
Weight/ω	0.30	0.22	0.25	0.23	
Amount of economic losses caused by heavy metal pollution/10,000 yuan	1397.9	1698.6	1745.8	1534.2	6376.5

adjust industrial structure. The government should change the energy structure and combustion methods in the northern areas of Shanxi Province, expand the application and use of liquefied petroleum gas, natural gas and other clean fuels. These initiatives can solve pollution problems caused by inefficient, highly polluting small-scale combustion facilities in the northern areas of Shanxi Province. Furthermore, measures should consider the complete elimination of the kiln, as well as shell and small furnaces that have low energy efficiency and seriously pollute urban environment. The government should also perform the following tasks: make technological transformation of existing heating boilers; improve thermal efficiency; meet emission standards; eliminate low-efficient dust collection equipment; actively develop highly efficient dust collector; further expand central heating area; optimize layout of heating; reduce energy consumption; and improve heat supply level and heating efficiency. Such methods can facilitate management departments to strengthen the use and management of dust collectors.

Enhancing heavy metal pollution prevention and control power of enterprises and stimulating the micro governance motivation: Given that many industrial enterprises are located in the northern areas of Shanxi Province, industrial enterprises should improve their environmental awareness and set heavy metal pollution prevention as an important decision-making factor. Meanwhile, government departments should actively encourage industrial enterprises to implement measures to prevent and control heavy metal pollution. Enterprises should emphasize direct economic benefits, given that indirect benefits brought bye co-friendly measures outweigh direct benefits. Only in this way can enterprises better grasp the impact of projects and make the best economic decisions. Industrial enterprises should implement the principle of coordinating economy with environment in business activities; ”combine prevention with control and focus on prevention”; prevent heavy metal pollution and achieve development of industrial production; and aim for environmental, social, and economic benefits. The active role of environment in business operations begins when companies start to pay attention to environmental protection. Such role can ensure sustainable development of industrial enterprises.

Improving laws on heavy metal governance by strictly implementing environment protection laws: The heavy metals in soil mainly come from air, water, and solid wastes. The heavy metals found in the soil of the northern areas of Shanxi Province, China also generated from these sources. Given that various pollutants cause varying degrees of heavy metal pollution in soil, local governments should develop urban soil environment protection program, organize urban ecological environment governance, and further implement special protection of urban agricultural land. The legal liability of heavy metal pollution prevention is an important part of the legal system of heavy metal pollution prevention and control, and is the most powerful method to prevent and control heavy metal pollution. Such measure clarifies the responsibilities of people or organizations that cause heavy metal pollution. Any enterprise or individual who causes pollution should pay huge fines, which can be used to finance fees for pollution control of heavy metal. Meanwhile, local governments should strictly implement various environmental laws, ensure that law enforcement is strict, and lawbreakers are prosecuted. Given thatching implements administration-led environmental protection, the power is relatively concentrated. Executive departments have significant discretion rights, thereby making legal supervision particularly important. Therefore, the government, executive departments, media, political parties, social organizations, ordinary people, and judicial departments should strengthen supervision over implementation of environmental laws.

Improving the heavy metal pollution environmental impact evaluation system by building supervision mechanism for prevention and control of heavy metal pollution: To improve the evaluation system of environmental impact caused by heavy metals, China should improve the environmental “cost-benefit” evaluation mechanism and quantify the environmental costs and efficiency indicators. This measure can provide enterprise with more references to evaluate the environmental economic feasibility of project in the production process and government regulation process. Industrial enterprises provide necessary materials for the development of certain regional resource and gain economic benefits. However, resources that are not fully utilized in this process can lead to heavy metal pollution in the environment. Heavy metal pollution is closely associated with manufacturing operations and inseparable from the regulation and supervision of government and environment protection departments. In the entire process of industrial enterprises, from selecting sites to construction, production, and pollution discharge and governance, the regulation on heavy metal pollution has always been the core of the environmental work of the government. This guideline can be the premise and foundation for enterprises to implement heavy metal prevention and control work. Government departments should improve the mechanism to evaluate heavy metal pollution of industrial enterprises, consider the configuration and benefits of environmental resources, and strengthen government responsibilities in preventing and controlling heavy metal pollution. In addition, measures should fortify accountability of heavy metal prevention and control, strengthen supervision and restriction of government power, use legal responsibility to regulate government behaviours, establish environmental information disclosure system for heavy metals in soil, and enable the public to participate in and supervise the prevention and control of heavy metal pollution.

CONCLUSION

This study analyses the spatial distribution of heavy metals in the soil of northern areas of Shanxi Province, and quantitatively calculates economic losses caused by heavy metal pollution in soil. A total of 96 sample data are obtained from 32 districts and counties in the study area. The Moran's I index of heavy metals in soil is calculated and the pollution loss rate model is adopted to determine the pollution loss rate of four common heavy metals in soil (i.e., Cd, As, Cu, and Cr) and the total amount of economic losses caused by pollution. The results indicate that the content indicators of Cd, As, and Cu in the northern areas of Shanxi Province have positive spatial correlation, whereas the spatial distribution of Cr has negative spatial correlation. The order of heavy metal pollution loss rate is Cr > As > Cu > Cd, and single heavy metal pollution loss rate is between 1.11% and 1.39%. The comprehensive heavy metal pollution loss rate is 5.24%, which belongs to Grade II in terms of pollution grade division. The economic loss caused by heavy metal pollution in soil is large, which is approximately 63.765 million yuan (RMB).

This study provides deep understanding on the current situation and spatial distribution of heavy metal pollution in the northern areas of Shanxi Province, the total amount of economic losses caused by heavy metal pollution in soil, and coordination of the relationship between economic development and environmental protection in the northern areas of Shanxi Province. Given that the distribution of heavy metals in soil is affected by industrial, transportation, and other human activities, heavy metal pollution in soil has various complex polluting sources. Hence, accurate computation of the amount of economic losses is difficult. Therefore, future research must increase soil samples, extend the species of calculated heavy metal pollution in soil, improve the economic loss model, and further explore whether economic losses caused by heavy metal pollution in soil are related to the economic level under different economic conditions.

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