Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268 e-ISSN: 2395-3454	Vol. 16	No. 3	pp. 947-952	2017

Original Research Paper

Open Access

Urban Heavy Metal-Polluted Soil Source and its Economic Loss Prediction: A Case Study on Changchun City in China

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

Received: 17-04-2017
Accepted: 18-07-2017

Key Words:
Heavy Metals
Soil pollution
Pollution source
Economic loss

ABSTRACT

Soil is an important component of the urban ecosystem environment and is polluted by all kinds of substances, such as heavy metals and organic matters from industrial production, daily life, and chemical fertilizers and pesticides. In this study, economic loss caused by soil heavy metal pollution was analysed using Changchun City in China as an example. First, the contents of four soil heavy metals (Cd, As, Cr, and Cu) and their variation trends in Changchun Automobile Economic and Technological Development Zone were explored. Then, the pollution loss rate mode was utilized to predict heavy metal pollution loss rate. Results show that the pollution loss rates of the four heavy metals are sorted as Cr, As, Cu and Cd in descending order and range from 1.12% to 1.41% with no major overall differences. A heavy metal pollution loss rate of 5.18% is classified as Grade II in pollution grading, which corresponds to a slightly clean level, but with a large economic loss of nearly USD 9,564,800. The study provides important references for further analysis of urban soil heavy metal sources, quantitative estimation of economic loss caused by soil heavy metal pollution, and implementation of evaluation work on soil environmental quality.

INTRODUCTION

Heavy metal elements are enriched and accumulated in the soil environment, cannot be degraded by microorganisms, and are pollutants characterized by stealthiness, universality, irreversibility, long endurance, indirect hazardousness, association, and comprehensiveness. A city is one of the important places that human beings occupy to engage in production and living activities. Soil is an important constituent part of the urban ecosystem and can directly or indirectly influence the urban environmental quality and health of urban people.

Changchun City, as the provincial capital of Jilin Province, China, is an industrial city in which human activities have brought a series of changes to the urban soil. Industrial "three wastes," household garbage, atmospheric dust fall, and rainfall generate inorganic substances (heavy metals), organic matters (organic solvents and hydrocarbons), and pathogenic bacteria (medical garbage), which result in soil pollution as well as changes of soil nutrient cycling and soil biological activities. In implementing projects, a few industrial development zones have not implemented environmental planning and evaluation of environmental quality and influence. Local governments also have reduced the reviews and approval links. All these factors have laid numerous potential hidden dangers for environmental quality and given rise to the occurrence of a series of problems endangering the environment and seriously affecting healthy development of the economic society. Research on the present soil environmental quality conditions surrounding several industrial zones in Changchun City, taken as an example, was conducted. Moreover, heavy metal pollution status and sources in the soil of urban industrial zones were investigated and economic loss caused by soil heavy metal pollution was analysed in this study. The aim was to timely master change orientation of soil environmental quality and thus determine the influence degree of urban industrial production on the urban environment.

Since the 1970s, many foreign scholars have started exploration. Albasel et al. (1985) investigated the soil heavy metals in the main expressways, industrial zones, and peri-urban grassland regions in Belgium and determined that the contents of Pb, Zn, Cu, and Mn in soil and plants rapidly decreased as the distance from the highway increased. Paterson et al. (1996) believed that the soil heavy metal element contents at two road sides were obviously higher than those in urban park, whereas the heavy metal contents in park soil were significantly higher than those in agricultural soil with the same parent material in exurb.

Zhang et al. (1999) deemed that the generated soil heavy metal pollution degrees were different because of the dissimilarities between influence strengths of human activities in cities. Higgs et al. (1999) thought that, the longer the history of the city, the higher the urbanization and industrialization levels and the higher the soil pollution degree. Nicholson et al. (2003) indicated that enriched heavy metals, such as Zn, Cu, and Cd, in agricultural soil mainly originated from atmospheric precipitation, sewer sludge, livestock dejection, pesticides, and irrigation water. Bhuiyan et al. (2010) analysed the current status of soil heavy metal pollution in coal mine and the generated loss in the northern region of Bangladesh. Li et al. (2014) assessed the loss caused by soil heavy metal pollution surrounding coal mines in China and evaluated its health risks. Ahmed et al. (2016) investigated the spatial distribution and sources of soil heavy metal pollution at the roadside of Dhaka Aricha expressway in Bangladesh. Marrugo-Negrete et al. (2017) evaluated the spatial distribution and origins of heavy metal pollution in agricultural soil in the Columbia River Basin. Zhang et al. (2006) believed that environmental pollution degraded the environmental quality and environmental resource values and certainly weakened the ecological service functions of the environmental system itself. Xu et al. (2009) analysed the heavy metal balance and health risk of the vegetable production system in the industrial urban-rural juncture area in the Yangtze River Delta in China. Libin et al. (2008) used the loss rate method to analyse the status of heavy metal pollution in vegetable soil in Fuzhou suburb. Shao et al. (2008) evaluated the status of soil heavy metal pollution in a typical area within the Yangtze River Delta. Yue et al. (2007) used the fuzzy comprehensive evaluation method to make a comprehensive analysis of soil environmental quality in Tongzhou District in Beijing. He et al. (2008) conducted a comparative study of soil heavy metal pollutions caused by e-waste recycling activity and traditional industrial operation. The previously presented studies indicate that the rapid urbanization has increased differentiation of urban functional zoning and human activities and that urban soil (particularly soil in the industrial zone) quality is closely related to human health and sustainable socio-economic development. Thus, research on the current soil environmental quality surrounding several industrial zones in Changchun City, taken as an example, was conducted and economic loss caused by soil environmental pollution was estimated. This study is an important reference for the analysis of soil heavy metal pollution sources and economic loss caused by pollution.

MATERIALS AND METHODS

Experimental design and soil sample analysis: Changchun City is in the middle-latitude north temperate zone in the northern hemisphere (125.35° E longitude and 43.88° N latitude), and its main urban area is on the Yitong River tableland inside Songliao Plain. The perimeter of the administrative area boundary is approximately 3,298.97 km. Changchun is located in Songliao Plain in the hinterland of the Northeast Plain on the east coast of Eurasia and is the natural geographic center of the northeast region, geometric center of Northeast Asia, and cross-shaped economic corridor center of Northeast Asia (Fig. 1). Since the early 1990s, Changchun City has accelerated automobile industrial production with obvious exhaust gas emission, enlarged the input quantity of chemicals (such as gasoline), and enhanced land use intensity; all these factors have resulted in serious soil pollution.

Fig. 1: Aerial view of the Changchun automobile economic and technological development zone.

A total of 98 sampling sites were set in the Changchun Automobile Economic and Technological Development Zone in this experiment. Soil samples were collected from each sampling site at six to nine plough layers (0-20 cm), mixed uniformly, reduced to 1-2 kg, and packed. After the soil samples brought to the laboratory were dried, impurities (such as stone and plant rootstock) were eliminated. Then, the samples were ground to 0.149 mm with an agate mortar for subsequent analysis. As content was determined through aqua regia digestion-atomic fluorescence spectrometry, heavy metals (such as Cd, Cr and Cu) were digested with HCl-HF-HNO_3-$HClO_4$ tetracid, Cd was determined through graphite furnace-atomic absorption spectrophotometry, and Cr and Cu were determined through inductive coupling plasma-atomic emission spectrometry. Each batch of samples (approximately 42 samples) and each item were determined through two standard samples, two parallel whole-course blanks, and 10% to 20% parallel samples to ensure the reliability and accuracy of analysis results.

Computation method of pollution loss rate: n heavy metals are assumed to exist in soil, and R_j is the heavy metal pollution loss rate caused by the j^{th} heavy metal to the soil. Establishing the differential formula between heavy metal concentration and economic loss of the soil environment is necessary to solve pollution loss rate R_j of the heavy metal, as shown in Formula (1):

$$\frac{dS}{dc_j} = \beta_j \frac{S}{K}(K - S) \qquad ...(1)$$

Where c_j is the mass concentration of heavy metal *j* in the soil (unit is mg kg^{-1}), *S* is the economic loss amount of soil heavy metal pollution when the mass concentration of heavy metal *j* is c_j (unit is USD 10,000), *K* is the economic value realized after soil utilization (unit is USD 10,000), and β_j is the proportionality coefficient of heavy metal *j* in the soil. The following expression is obtained by solving Formula (1):

$$S(c) = \frac{K}{1 + \alpha_j \exp(-\beta_j c_j)} \qquad ...(2)$$

Formula (2) conforms to the logistic formula and is the economic loss model of pollution caused by heavy metal *j*, where, α_j is a constant term obtained during the solving process. For simplification of the model, the following expression is derived:

$$R_j = \frac{1}{1 + \alpha_j \exp(-\beta_j c_j)} \qquad ...(3)$$

Moreover, $S = KR_j$, where R_j is the loss rate caused by heavy metal j to the soil environment and is called the pollution loss rate of a single heavy metal. In Formulas (2) and (3), α_j and β_j are constant terms during the solving process (α_j>0), related to the pollution characteristics of heavy metals, and determined generally through toxicity experiments of heavy metals or actual investigations on polluted environmental resources. Damage caused by heavy metals to soil is reflected by its influence on the corresponding plants and animals preying on plants. This method is relatively reasonable but involves considerably complicated problems. Moreover, no whole set of definite data is available at present. Half of the primary standard (representing natural background value) in the China Heavy Metal Mass Standard for Soil Environment (GB 15618-1995) was taken as criterion for determining parameters and α_j and β_j, as given in Table 1

Concrete steps are setting the background concentration of the j^{th} heavy metal in the environment as c_{oj}, the corresponding pollution loss rate of a single heavy metal as R_{oj}, and the corresponding pollution loss rate of a single heavy metal as R_{tj}. Then, these variables are substituted into Formula (3) to obtain the following system of binary linear formulas:

$$\begin{cases} R_{oj} = \dfrac{1}{1 + \alpha_j \exp(-\beta_j c_{oj})} \\ R_{tj} = \dfrac{1}{1 + \alpha_j \exp(-\beta_j c_{tj})} \end{cases} \qquad ...(4)$$

For convenience of expression, the following equation is defined:

$$f_j = \ln \frac{R_{tj}(1 - R_{oj})}{R_{oj}(1 - R_{tj})} \qquad ...(5)$$

The following equation can be solved in accordance with Formulas (4) and (5):

$$a_j = \left[(1 - R_{oj}) / R_{oj}\right] \exp\left[f_j c_{oj} / (c_{tj} - c_{oj})\right] \quad \text{or}$$
$$a_j = \left[(1 - R_{tj}) / R_{tj}\right] \exp\left[f_j c_{tj} / (c_{tj} - c_{oj})\right], \quad \beta_j = f_j / (c_{tj} - c_{oj}) \qquad ...(6)$$

When multiple heavy metals act on soil environmental resources, the joint effect of multiple heavy metals is not only the simple addition of the single actions of these heavy metals. The economic loss model of soil heavy metal pollution regards multiple heavy metals as an organic connection. The comprehensive heavy metal pollution loss rate is inferred following set theory and probability theory. If two heavy metals A and B exist in soil, then the corresponding loss rates of single heavy metals are R_A and R_B, respectively. The probabilities of A and B are equal to the amount obtained by reducing the product of the probabilities of the two events from the sum of the probabilities of the two events, that is, $R_{AB} = R_A + R_B - R_A \cdot R_B$. The comprehensive heavy metal pollution loss rate *R* of the n^{th} heavy metal is obtained through recursion as:

$$R = 1 - \prod_{j=1}^{n} (1 - R_j) \qquad ...(7)$$

However, the weights of heavy metals are different; thus, they differ in their contribution rates to the comprehensive heavy metal pollution loss rate. Therefore, Formula (7) was modified by considering the difference of the weights of heavy metals. The weights of heavy metals were determined using the principal component analysis method in multivariate statistical analysis. The concrete steps of the method are as follows. First, the eigen values and contribution rates of the principal components of heavy metals are solved and the contribution rates of the first two principal components that have met the requirements for information extraction are determined. Then, the corresponding load matrixes are calculated, the common factor variances of heavy metals are solved, the variance values representing the contribution rate to comprehensive variation are determined, and the weights of heavy metals are calculated using the variance values.

Table 1: Soil heavy metal pollution grading (unit: mg·kg^{-1}).

Heavy metal	Grade I (clean)	Grade II (slightly clean)	Grade III (mild pollution)	Grade IV (moderate pollution)	Grade V (heavy 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: Parameter determination of the economic loss model of soil heavy metal pollution.

	Cd	*As*	*Cr*	*Cu*
α	274	359	302	259
β	5.091	0.153	0.024	0.023

Table 3: Classification standard of the soil heavy metal pollution loss rate.

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

$$R = 1 - \prod_{j=1}^{n}(1 - R_j \omega_j n) \quad ...(8)$$

Where ω_j is the weight of the j^{th} heavy metal and *n* is the kind of soil heavy metal. Economic value loss that pollution of heavy metal *j* caused to soil is set as

$$S = KR \quad ...(9)$$

Finally, economic value loss is converted into USD 10,000 in accordance with the USD/Renminbi exchange rate of 6.8958 on December 1, 2016.

EXPERIMENTAL RESULTS

The soil baseline line in Changchun Automobile Economic and Technological Development Zone is considered as the background concentration. The heavy metal pollution loss rates of single heavy metal *j* under the background concentration state of the critical state of heavy pollution are assumed to be 1% and 99%, respectively. Parameters α and β are calculated following Formula (6), and the results are presented in Table 2.

In accordance with the grading standard of soil heavy metal pollution degrees in Table 1 and the α and β values in Table 2, the ranges of the comprehensive heavy metal pollution loss rates at different pollution grades of heavy metals are calculated. The results are given in Table 3.

The pollution loss rates of single heavy metals, the comprehensive heavy metal pollution loss rates, and the comprehensive economic loss amounts are calculated in accordance with Formulas (3) and (9). The results are depicted in Table 4.

Table 4 shows that the pollution loss rates of single heavy metals are sorted as Cr > As > Cu > Cd. The corresponding weights are $\omega(\text{Cr}) = 0.21$, $\omega(\text{As}) = 0.27$, $\omega(\text{Cu}) = 0.20$, and $\omega(\text{Cd}) = 0.32$. The pollution loss rates of single heavy metals are within 1.12% to 1.41%, with only a slight overall difference. The comprehensive heavy metal pollution loss rate is 5.18%, which is classified as Grade II (slightly clean) in pollution grading level according to the classification standard in Table 3. Moreover, the economic loss amount caused by soil heavy metal pollution is large at approximately USD 9,564,800.

The empirical results show that environmental protection principles of "prevention centered and prevention and treatment integrated" for soil pollution must be adhered to. Controlling and eliminating soil pollution sources constitute the basic measure preventing pollution. The purifying capacity of soil for pollutants is equivalent to certain processing capacity. Controlling soil pollution sources means controlling the quantity of pollutants entering soil and their speed, and the natural purification effect can be exerted to prevent soil pollution. Closed cycle and nontoxic technology should be vigorously promoted to reduce or eliminate pollutant discharge. Industrial "three wastes" should be recycled to turn harm into good effects. The already discharged "three wastes" should be purified, and the pollutant discharge amount and concentration of pollutants should be strictly controlled to meet the discharge standard. In sewage irrigation area, water quality monitoring of irrigation sewage should be strengthened. Moreover, the components, contents, and dynamics of pollutants in water should be understood to prevent pollutants carrying nondegradable high residues from entering the soil and causing soil pollution.

Highly toxic and persistent pesticides should be forbidden or restricted, and high-efficiency, low-toxicity, and low-

Table 4: Soil heavy metal pollution loss rates and economic pollution loss amounts.

	Cd	*As*	*Cr*	*Cu*	Comprehensive
Heavy metal loss rate/%	1.12	1.26	1.41	1.16	5.18
Weight/ω	0.32	0.27	0.21	0.20	-
Economic loss amount of heavy metal pollution/USD (10,000)	211.45	250.24	267.15	227.65	956.48

residue pesticides should be developed. Moreover, biological control and prevention measures, such as forbidding pesticides with low residue, but with acute and high toxicity and forbidding high-residue organochlorine pesticides, should be implemented. Chemical pesticides should be reasonably applied depending on their characteristics, and the safety interval of pesticide application should be formulated. Comprehensive preventive measures should be taken not only to prevent the threat posed by pests to crops but also to restrict the harm caused by pesticides to the environment and body health to the minimum level. The contents of soil organic matters should be increased to improve the kinds and quantities of soil colloids and enhance the adsorption capacity and quantity of soil for hazardous substances to reduce the activity of pollutants in soil. New microorganism varieties should be discovered, separated, and cultured to enhance the biodegradation effect, which is an important link to improve the soil purification capability. Regular checks of soil environmental quality should be conducted in the area under administration, archival data of the system should be established, and priority detection and detection standards and methods of soil pollutants should be stipulated. Control objectives of soil environmental pollution can be compiled with a reference to suggestions of international organizations and China's national conditions. Investigation, research, and policy implementation should be conducted depending on priority ranking.

Soil cultivation can change the soil environmental conditions and eliminate the harm of some pollutants. Rice field-upland field rotation can be implemented to alleviate and eliminate pesticide pollution effectively. The transformation of dry farmland into paddy field slowly degrades the pesticides in dry farmland with large residual amount and obvious accumulation. DDT degradation in paddy farmland is accelerated, and rice field-upland field rotation according to this property is an effective measure that can alleviate or eliminate agricultural pollution. Soil pollution, particularly caused by heavy metals, accumulates in soil and hinders the growth and development of crops. The fundamental prevention and control method is the soil damping and dressing method, which radically excavates the polluted soil layer and replaces it with new soil to eradicate pollutants. However, using the soil dressing method is impractical for regional pollution. The soil layer should be ploughed up, that is, deep ploughing, turning over, and mixing of the upper and lower soil layers, such that pollutant content in surface soil will be reduced. This method has a small earth moving quantity but is inappropriate for use in seriously polluted areas.

Biological concentration can occur to heavy metals, thereby causing significant potential hazards to human beings. Moreover, if air and water bodies are polluted, then pollution problems may be continuously reversed through the dilution and self-purification effects after pollution sources are cut off. However, eliminating non-degradable pollutants that accumulated in polluted soil by depending on dilution and self-purification effects is difficult. Once soil pollution occurs, recovering only by depending on cutting off pollution sources is difficult. Sometimes, problems can be solved only through methods, such as soil replacement and washing off, although other governance techniques may produce the desired result gradually. Therefore, governance of polluted soil is generally of high cost and long governance cycle. An important path for heavy metals to enter soil is using wastewater containing heavy metals for irrigation, and another path is through atmospheric sedimentation. The construction of a soil pollution prevention and control system has proposed concrete measures and responsibilities for enterprises and governmental sectors. Close cooperation is needed between enterprises and governmental sectors.

CONCLUSION

Human activities cause heavy metals to enter soil and accumulate to a certain degree, which will cause harm to soil ecosystem and the degradation of environmental quality. These phenomena directly or indirectly threaten human health through the food chain.

In this study, Changchun City in China was taken as an example. First, the contents of four soil heavy metals (Cd, As, Cr, and Cu) and their variation trends in Changchun Automobile Economic and Technological Development Zone were analysed. Then, the pollution loss rate mode was utilized to predict the heavy metal pollution loss rate. The experimental results indicate that the pollution loss rates of the heavy metals are sorted as Cr, As, Cu, and Cd in descending order and range from 1.12% to 1.41% with no major overall differences. A heavy metal pollution loss rate of 5.18% is classified as Grade II in pollution grading, which corresponds to a relatively clean level with a large economic loss amount of approximately USD 9,564,800. In-depth research should be conducted to improve the relationships between soil heavy metal pollution sources and human activities, such as soil environmental quality standard, transportation layout, land utilization type, metal distribution in soil, and industrial transportation, and further improve research accuracy and reliability.

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