Comprehensive assessment of regional selenium resources in soils based on the analytic hierarchy process: Assessment system construction and case demonstration

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HIGHLIGHTS

- A comprehensive assessment of regional selenium resources was constructed by AHP.
- Soil selenium, nutrient and environmental quality were indexes in criterion layers.
- The criterion was classified by summing critical values in standards with weights.
- The comprehensive evaluation system of selenium was classified into 5 grades.
- Priority areas for developing selenium-rich agriculture were identified in Boshan.

GRAPHIC ABSTRACT

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ABSTRACT

The redundancy or deficiency of selenium in soils can cause adverse effects on crops and even threaten human health. It was necessary to assess selenium resources with a rigorous scientific appraisal. Previous studies of selenium resource assessment were usually carried out using a single index evaluation. A multi-index evaluation method (analytic hierarchy process) was used in this study to establish a comprehensive assessment system based on consideration of selenium content, soil nutrients and soil environmental quality. The criteria for the comprehensive assessment system were classified by summing critical values in the standards with weights and a Geographical Information System was used to reflect the regional distribution of the assessment results. Boshan, a representative region for developing selenium-rich agriculture, was taken as a case area and classified into Zone I–V, which suggested priority areas for developing selenium-rich agriculture. Most parts of the North and Midlands of Boshan were relatively suitable for development of selenium-rich agriculture. Soils in south fractions were contaminated by Cd, PAHs, HCHs and DDTs, in which it was forbidden to farm. This study was expected to provide the basis for developing selenium-rich agriculture and an example for comprehensive evaluation of relevant resources in a region.

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1. Introduction

As an essential nutrient element, selenium was confirmed to have many benefits in human health, such as improving immunity, delaying senescence, preventing cancer and cardiovascular disease (Hatfield et al., 2014; Hughes et al., 2015; Stolzoff and Webster, 2015). Many epidemic diseases, such as Keshan disease, were caused by selenium deficiency in soils (Listed, 1979; Loscalzo, 2014). Previous studies focused on ecological risk of selenium for human health or selenium deficiency risk in populations (BY and XL, 2000; Skalny and Burtseva, 2015) and on how to replenish selenium. People may solve the self-demand for selenium by eating agricultural Se-enriched products. However, an overdose of selenium caused toxicity on living organisms, which may also have potential risks in ecosystems (Huang et al., 2009; Zhang et al., 2008).

Soils are the basis of plant growth and supply water and essential mineral elements, including selenium. In order to increase the concentrations of selenium in crops and vegetables, the farmers usually choose to do farming in some seleniferous soils, and fertilizers enriched with selenium could be another option to increase selenium concentrations in soils which lack selenium (De Temmerman et al., 2014). The investigation and assessment of selenium resources in soils could be a good guide to develop selenium-rich agricultural bases, which addresses the demand for selenium. However, past studies focused on a single index evaluation of selenium resources in farmlands (Li et al., 2006; Yang et al., 2016). Compared with single-index assessment, the multi-index assessment represents the states of soils more systematically and comprehensively. The growth of crops was affected by many factors, such as soil nutrients and environmental quality. It is necessary and meaningful to investigate and assess selenium in soils regionally and comprehensively.

The Analytic Hierarchy Process (AHP) is a multi-target decision method, which decomposes complex problems into different elements and classifies these elements into different levels (Saaty, 1980; Saaty, 2005; Saaty, 2008). AHP was usually applied to make a decision to select a suitable site with different purposes for environmental management (Hajeesh and Al-Othman, 2005; Vahidnia et al., 2009; Wang et al., 2009). The AHP approach was also adopted by many researchers for agricultural decisions (Alphonse, 1997). For example, the sites were chosen for agricultural management practices, such as forage fields, based on AHP (Sun et al., 2009). Therefore, AHP could be a promising tool to assess selenium resources and select sites for development of selenium-rich agriculture.

This study planned to combine a specialized analysis with visualization tools to assess selenium resources on a regional scale. Based on the AHP and the Geographic Information System (GIS), a comprehensive assessment system of regional selenium resources was constructed through considering three aspects: selenium resources, soil nutrients, and environmental quality. In this way, soil nutrient factors, selenium and pollutant content in soils were analyzed and determined. This study is expected to provide the basis for development of selenium-rich agriculture, but also to provide a reference example for the comprehensive evaluation of regional environmental resources.

2. Assessment methods and procedures

2.1. Frame for regional selenium resources assessment

The main aim of this study was to evaluate selenium resources in soils and construct a comprehensive evaluation system of regional selenium resources based on AHP. The general steps of AHP are to establish the analytic hierarchy structure, construct the judgment matrix to determine the weight of each index, and calculate the weight of each evaluation factor. Firstly, we need to determine the evaluated unit of a regional area. At the same time, the analytic hierarchy process was used to establish hierarchical structure of the assessment system and

to identify each index level. The soil samples were collected and analyzed from each unit in the region to obtain measured data. Then, these measured data were standardized to eliminate effects of different dimension. In order to determine weights of each index level, experts and scholars with a background in ecology or environmental science were invited to answer the questionnaires to determine the weight of each index using the AHP and Delphi method. The comprehensive assessment index of each unit was calculated. The criteria proposed by experts and scholars and the national standards of China offered references for establishing assessment criteria of regional selenium resources. Next, the comprehensive evaluation system of regional selenium resources was classified into different grades. The measured data were standardized using a non-dimensionalized method, and then the standardized values were interpolated by a geographic information system (ArcGIS 10.2) to reflect spatial distribution characteristics on a regional scale. According to sampling distribution and the size of samples, the suitable spatial interpolation method was adopted. When sample points normally follow the uniform distribution and the size of sample is relatively large, inverse distance weighting (IDW) will be adopted. According to the assessment criteria, evaluated areas were classified into corresponding zones and spatial distribution maps were produced to reflect the evaluation results. Through analyzing the evaluation results, reasonable suggestions were provided for the development of selenium-rich agricultural soils. A flow chart showing the research process is seen in Fig. 1.

2.2. Establishing hierarchical structure

To develop selenium-rich agriculture, we need to consider the content of selenium, environmental quality and soil nutrients, which are important factors that affected the growth of selenium-rich crops and the selenium content in plants. According to the principles of scientific, feasibility, compatibility and comprehensiveness of the analytic hierarchy process, indicators were selected and the hierarchical structure of the assessment system was established. The analytic hierarchy process usually contains three levels: target layer, criteria layer and index layer. The target layer was the comprehensive evaluation system of regional selenium resources. This study aimed to evaluate selenium resources in the region generally and scientifically. The selenium content, soil nutrients and environmental quality were chosen as indexes in the criterion layers of the hierarchical structure. Selenium was the subject of assessment and it was considered necessary and meaningful to evaluate selenium content in soils. In general, high soil nutrient content promotes crops growth and increases the volume of crops production. The good state of soil environmental quality is the guarantee of food safety as pollutants in soils can enter the human body through the food chain, which may cause human health problems (Gergen and Harmanescu, 2012; Khan et al., 2008). Therefore, soil environmental quality should be taken into account and chosen as an index in the comprehensive evaluation system of regional selenium resources.

In the criteria layer, the total selenium content in surface soils was selected as an indicator of the index layer. The total selenium content in surface soils was the result of the weathering of the parent material and the enrichment of the plants, which was regarded as an indicator that reflects selenium content in a region. Except total selenium content, bioavailable selenium is also related to the enrichment or deficiency of selenium. However, since the classification of bioavailable selenium is still controversial according to different extraction methods (Tolu et al., 2011; Li et al., 2016) and evaluation systems and standards of bioavailable selenium remain to be updated, bioavailable selenium was not chosen as an evaluation index. In the criteria layer of soil fertilizer, the content of soil organic matter, soil clay and soil nitrogen were chosen as indexes of the index layer. These environmental factors not only affect the plant growth, but also have impacts on effectiveness and speciation of selenium (Johnsson, 1991; Borowska et al., 2013; Supriatin et al., 2015). Soil organic matter, soil clay and soil nitrogen are important

Fig. 1. Flow chart of comprehensive assessment of regional selenium resources.

indicators of soil nutrient and fertility, which play important roles in improving soil physical and chemical properties that affect growth. Besides, soil organic matter, total nitrogen, and clay content may affect the absorption of selenium in plants (Supriatin et al., 2016). Under the criteria layer of soil environmental quality, the contents of heavy metals, polycyclic aromatic hydrocarbons (PAHs) and pesticides (DDTs and HCHs) were identified as indicators of the index layer. These pollutants are basic control indicators in environmental quality evaluation standards for farmland of edible agricultural products and environmental quality standards for soils (State Standard of China, 2006). It is also noteworthy that the compound pollution of pesticide, heavy metal and polycyclic aromatic hydrocarbons were found in many areas of China (Shen et al., 2005; Sun et al., 2014). Previous studies reported that selenium was associated with some other mineral elements, including arsenic, cadmium and lead (Tian et al., 2016), and these heavy metal elements were classified as heavy metal type I. Other heavy metal elements, which are not associated with mineral elements and may cause heavy metal pollution in local areas, were classified as heavy metal type II. These elements, which were chosen as evaluation indexes, would be selected according to an investigation into heavy metal elements in the study area.

2.3. Weight determination

By using the Delphi method and a questionnaire survey, the opinions of experts and scholars were collected (Vidal et al., 2011). Participants assessed pairs of elements in the same layer based on their relative importance to the upper hierarchy. Then, experts and scholars determined their relative importance of the element and gave corresponding scores according to 9-point scales respectively (Saaty, 2000). In this way, the importance was transformed into the corresponding numerical value and the judgment matrix was constructed.

The judgment matrix was normalized first, and then the eigenvalues and eigenvectors of the normalized matrix were calculated to find the maximum eigenvalue. The consistency ratio (CR) was utilized to verify the consistency of the judgment matrix (Hsu et al., 2008). The consistency of the judgment matrix was checked. When CR was <0.1 , it was considered that the single level judgment matrix had satisfactory consistency (Kang and Seong, 1999; Kaya and Kahraman, 2010). If the consistency test passed, the weight of each index was obtained. If the consistency test failed to pass, the judgment matrix continued to be coordinated till it meets the consistency check. For the criteria layer, CR was computed firstly and checked whether it passed the consistency test. In addition, the corresponding weight of each element in the criteria layer was determined. Using the same method and steps, the respective judgment matrixes of soil fertility and environmental quality were constructed. Afterwards, the respective eigenvalues and eigenvectors were obtained to check whether the value of their CR met the consistency test. If the results of all judgment matrices are acceptable through consistency test, the consistency check of total sequencing of each level is applied. With satisfactory consistency, each index weight of the comprehensive environmental selenium resources regional evaluation was confirmed.

2.4. Standardization of evaluation index and calculating comprehensive index

Applying multi-indicators assessment, the comprehensive analysis and assessment was difficult to conduct because indicators had different dimensions and the values of different indexes also had relatively large differences. Therefore, the data of each evaluation index needed to be dimensionless. The min-max normalization method was adopted to eliminate effects of different dimension (Du, 2016; Yin, 2013). When the concentration of selenium in surface soils was below 3 mg/kg, the

index of selenium resources was regarded as the positive indicator, which was standardized using formula (1). When the concentration of selenium in surface soils was above 3 mg/kg, the measured value was standardized by formula (3). This conversion guaranteed the zones obtained very low comprehensive scores because selenium may cause adverse effects on crops and pollute the soils when concentrations were >3 mg/kg (Tan et al., 1987). Indexes of soil fertility were seen as positive indicators, which were standardized using formula (1). The concentrations of various pollutants in the soil environment were regarded as negative indicators, which were transformed using formula (2). The more serious the pollution, the smaller the value.

$$R_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \times 100 \quad (1)$$

$$R_i = \frac{x_{\max} - x_i}{x_{\max} - x_{\min}} \times 100 \quad (2)$$

$$R_i = \frac{0.375/x_i - x_{\min}}{x_{\max} - x_{\min}} \times 100 \quad (3)$$

i represents sample serial number; R_i is non-dimensionalized value after conversion by min-max normalization method; x_i is the i^{th} measured value, $x_{\max}$ is the maximum of all measured values, $x_{\min}$ is the minimum of all measured values.

According to the weights and the dimensionless value of each evaluation factor, a comprehensive index (D) was calculated in evaluation units. The composite index was calculated following formula (4). The larger the comprehensive index (D), the corresponding zones were more suitable for developing selenium-rich agriculture. Calculating comprehensive evaluation indexes, classifying grades and drawing maps were all operated in ArcGIS 10.2 for windows 10.

$$D = \sum W_i R_i \quad (4)$$

i represents sample serial number; D represents the comprehensive evaluation index; R_i is nondimensionalized value after conversion by min-max normalization method; W_i is corresponding weights.

2.5. Comprehensive evaluation criteria

The critical values in quality standards, soil fertility criteria and ecological landscape classification of selenium (Table S1, in supplementary material) were selected to calculate new critical values for comprehensive assessment (Tan et al., 1987; National Soil Survey Office, 1992; State Standard of China, 2006; Sun et al., 2016). The critical values in original standards were non-dimensionalized because the dimension of different indexes is different. The new critical values of a comprehensive evaluation system of regional selenium resources were calculated by summing standardized critical values with corresponding weights, as shown in the following formula (5).

$$S = \sum W_i C_i \quad (5)$$

i represents sample serial number; S represents critical values of comprehensive evaluation system of regional selenium resources. C_i is the nondimensionalized critical value after conversion by min-max normalization method; W_i is the corresponding weight.

This criterion for the specific classification followed the principles that we considered as below. In zone I, soils must be clean and processed with rich selenium resources and high fertility, which is recommended for developing selenium-rich agriculture. The region, which was detected with pollutants exceeding environmental quality standard, was directly assigned into rank V. The areas, in which selenium content exceeded 3 mg/kg, were also sorted into rank V. Selenium may cause diseases and toxicity when it is in soils beyond 3 mg/kg or goes below 0.125 mg/kg (Tan et al., 1987, Tan and Zhu, 1989). The

classification from II to IV was mainly based on critical values for comprehensive assessment. Zone II and III were allowed to develop selenium-rich agriculture, while Zone IV was not suitable to develop selenium-rich agriculture. Based on the cited standards with a five level ordinal scale, the comprehensive evaluation system of regional selenium resources was classified into 5 grades (Table 1).

3. Case study on comprehensive assessment of regional selenium resources

3.1. General situation of case area

Boshan was taken as a case area, as it is regarded as a representative base for developing selenium-rich agriculture in North China. The average content of selenium in this area is 0.305 mg/kg, which is slightly higher than the national average (0.290 mg/kg). The case area is Boshan district, located in Zibo city, Shangdong province, China, which lied between the north latitude 36°16'–36°31' and the east longitude 117°43'–118°42' (Fig. 2). The total area of Boshan district is 698.2 km². The general terrain is highlands in the South and lowlands in the North. The northern terrain is mostly hilly with valleys and mid-low mountains located in the eastern, western and southern parts. In Boshan, the 4 main rivers are Zi River, Xiaofuhe River, Qingyang River and Niujiao River, from which farmland can be irrigated. The average annual precipitation in this region is 736.6 mm and the maximum precipitation occurs during the summer. The annual temperature ranged from −2.2 °C to 27.5 °C and the average annual temperature was 13.6 °C.

3.2. Sample collection and analysis

The sampling process used the uniform grid method with a 3 * 3 km grid in the Boshan area (Fig. 2). The surface soils (0–20 cm) were collected and the total number of samples was 61. GPS was used to locate the sample and the soil samples were taken back to the laboratory and dried in the shade. In order to obtain the relevant data, physical and chemical properties of soils, the content of selenium, heavy metals and polycyclic aromatic hydrocarbons (PAHs) were analyzed for all samples. Pesticides (DDTs and HCHs) were analyzed for 16 samples in the agricultural region and the spatial interpolation method was used in the rest of the case area to obtain corresponding content of pesticides (DDTs and HCHs).

The contents of selenium in surface soils were determined by microwave digestion and the atomic fluorescence method. No selenium was detected in blank control and analytical quality control was used in this experiment. In order to guarantee the accuracy, the national standard soil reference (GSS-3) was also analyzed and the measured mean of selenium content was 0.093 mg·kg^{−1}, which showed that the measured data were reliable. The soil sample was firstly heated by oil bath and the potassium dichromate titration method was used to determine total organic carbon (TOC) content. Total nitrogen (TN) in the soil samples was determined by elemental analysis instrument. After pretreatment, the content of clay was measured using laser particle size

Table 1

Classification criteria of a comprehensive evaluation system of regional selenium resources.

Classification	S	Features
I	>60	Recommend for the development of selenium-rich agriculture
II	32–60	Relative suitable for development of selenium-rich agriculture
III	24–32	Allow the development of selenium-rich agriculture
IV	18–24	Not recommended for selenium-rich agriculture
V	<18	Forbid the development of selenium-rich agriculture

S represents critical values of comprehensive evaluation system of regional selenium resources.

Fig. 2. Location of case area and sampling distributions.

analyzer. The concentrations of heavy metal elements were measured using microwave digestion and inductively coupled plasma mass spectrometry (ICP-MS). Determination of DDTs and HCHs was measured by gas chromatography and polycyclic aromatic hydrocarbons (PAHs) were determined by liquid chromatography. In the above measurement process, the quality control was carried out by using control groups, parallel samples and standard samples.

3.3. Questionnaire survey

Based on the comparative importance using AHP, questionnaires were designed to determine the weight of the indexes. Before answering the questionnaire, participants were informed about the soil investigation data of Boshan, including selenium content, soil nutrients and pollutant contents. Experts and scholars were invited to fill in questionnaires about factors comprising the criterion layer and index layer in pairs by the Delphi method. According to the degree of importance, the corresponding scores were obtained and the judgment matrix was constructed. Twenty questionnaires were distributed to experts and scholars with knowledge of selenium, and twenty questionnaires were distributed to experts and scholars with knowledge of soil science. Another twenty questionnaires were distributed to specialists in environmental science. A total of 60 questionnaires were collected and the number of valid questionnaires was 52.

3.4. Hierarchical structure and calculation of weights

The results of comparing the relative importance of the criteria layer elements are shown in Table 2. The judgment matrix of each sub layer was derived by following the same method and procedure (Table 3). According to the judgment matrix, the Yaahp software was used to calculate the weight (Chen and Shen, 2012; Nie et al., 2013; Wu et al., 2014). After a series of calculations, the CR of the criteria layer was 0.0089, which is <0.1 and satisfied the consistency test.

According to the analytic hierarchy process, hierarchical structure was established as shown in Table 4. This assessment system consists of 1 target layer (A), the 3 criteria layers (B) and the 9 index layer (C). Weights of each index were also determined in Table 4.

Table 2
Results of comparing relative importance in criteria layer(B).

	Selenium resources	Soil fertility	Environmental quality
Selenium resources	1	3	2
Soil fertility	1/3	1	1/2
Environmental quality	1/2	2	1

3.5. Measured data of assessment indicators

Measured data of each sample were presented in Fig. 3. All the measured values of selenium content were <3 mg/kg and selenium was beneficial to agricultural production (Fig. 3(a)). Most measured data of TOC ranged from 0 to 2 g/kg (Fig. 3(b)). Five samples had a relatively high content of TOC, which implied high organic matter content in these areas. As shown in Fig. 3(c), TN concentration was 0.5 and 1.5 g/kg. The soil types in the case area were loam and clay (Fig. 3(d)). The phenomenon that pollutants exceed the environmental quality standard occurred in a few areas in Boshan and the pollutants were heavy metal Cd and PAHs. HCHs and DDTs were also beyond the limit of farmland environmental quality evaluation standard for edible agricultural products in fractions of Boshan (State Standard of China, 2006). This pollution problem may be caused by pesticide residues (Fig. 3(h) and (i)). Although HCHs and DDTs have been banned for many years, they were slow to degrade in the natural environment.

3.6. Evaluation results and suggestions

The evaluation results of each criterion layer are shown in Fig. 4. As shown in Fig. 4(a), the content of selenium had a decreasing tendency from north to south in the case area. The selenium content was affected by many factors, including selenium content in soil parent material, physical and chemical properties of soils. Previous studies reported that selenium was accompanied with mineral elements (Chen et al.,

Table 3
Results of comparing relative importance in index layer(C).

	TOC	TN	Clay	Cd ^a	Cr ^b	PAHs	HCHs	DDTs
TOC	1							
TN	1/4	1						
Clay	1/3	2	1					
Cd ^a				1				
Cr ^b				1/5	1			
PAHs				1/3	1/3	1		
HCHs				1/3	1/2	3	1	
DDTs				1/4	1/2	3	1	1

^a Cd was chosen as a representative for heavy metal type I in the case study. Heavy metal type I represents the heavy metals, which may be accompanied with mineral elements in soils, are likely to cause pollution. The content of Cd is significantly correlated to the content of Se in the case area;

^b Cr was chosen as a representative for heavy metal type II in the case area. Heavy metal type II represents other heavy metals, which would cause pollution. The content of Cr is uncorrelated to the content of Se and its content is relatively more than other heavy metals.

Table 4
Comprehensive evaluation system of regional selenium resources and corresponding weights.

Target layer	Criterion layer	Weight	Index layer	Weight	Total sequencing weight
Comprehensive evaluation system of regional selenium resources	Selenium resources	0.539	Se	1.000	0.539
	Soil fertility	0.164	TOC	0.623	0.102
			TN	0.137	0.023
			Clay	0.240	0.039
	Environmental quality	0.297	Cd ^a	0.454	0.135
			Cr ^b	0.195	0.058
			PAHs	0.073	0.022
			HCHs	0.143	0.042
			DDTs	0.135	0.040

^a Cd was chosen as a representative for heavy metal type I in the case study. Heavy metal type I represents the heavy metals, which may be accompanied with mineral elements in soils, are likely to cause pollution. The content of Cd is significantly correlated to the content of Se in the case area;

^b Cr was chosen as a representative for heavy metal type II in the case area. Heavy metal type II represents other heavy metals, which would cause pollution. The content of Cr is uncorrelated to the content of Se and its content is relatively more than other heavy metals.

2015). Our previous study found that Se in soils of Boshan was significantly correlated with Cd. There were hundreds of coal mines in the midlands of Boshan in the past few decades. The extraction of coal may accelerate weather of Se-bearing rocks, which led to higher concentration in soils (Ryser et al., 2006). Considering the overall region, northern areas had been higher fertility of soils than the south

(Fig. 4(b)). In western zones, the soils were clean and fertile but the selenium content was low, which suggested this region was used for agricultural land uses. In the northeast zones for urban and industrial land uses, the environmental quality was relatively poor (Fig. 4(c)), which may cause soil pollution due to the release of pollutants from domestic and industrial activities. The environmental quality was also relatively poor in several parts of the southern areas, especially in southeast zones. This pollution may have been caused by continued overuses of pesticides in the farmlands.

The results of comprehensive evaluation of regional selenium resources in Boshan are shown in Fig. 5. Zone I was the most suitable for developing selenium-rich agriculture, which was 1.92 km². This area is rich in selenium resources, with clean and fertile land, which was recommended for the development of selenium-rich agriculture. Zone II was 258.44 km² and accounted for 37.02% of total area, and is mainly distributed in western and northern zones. Zone II was relatively suitable for the development of selenium-rich agriculture because selenium content was relatively high and soil nutrients are abundant. Zone III occupied the largest area in Boshan (393.72 km²). In this region, selenium content reached an adequate level. However, to develop selenium-rich agriculture in Zone III (393.72 km², 56.39% of total area), selenium-rich agriculture will be developed only by applying exogenous selenium fertilizer. Zone IV covered 42.23 km² and accounted for 6.07% of total area in Boshan. The soils in this area are relatively clean, which complies with Chinese soil environmental quality standard. However, the selenium content and soil fertility are relatively low in the soils of Zone IV, which is not suitable for developing selenium-rich agriculture. It is suggested that pioneer and accompanying species may be developed in Zone IV. Zone V was 1.89 km² and accounted for 0.3% of total area.

Fig. 3. Measured data of assessment indicators.

Fig. 4. Assessment results of selenium resources (a), soil nutrient (b) and environmental quality (c) in Boshan.

Selenium-rich agriculture was forbidden in Zone V, which comprised small fractions located in south zones. Low selenium content was detected in these fractions. In addition, the land was impoverished and polluted. This pollution problem may have been caused by heavy metal Cd, PAHs, HCHs and DDTs. If we want to develop agriculture in this region, it will be necessary to recover and remediate the pollution in soils as soon as possible. The assessment results suggested that only 6.37% of the land was totally unsuitable or forbidden to develop selenium-rich agriculture. Selenium-rich agriculture could be developed in most areas, especially in the North and Midlands.

4. Conclusions

Boshan in Shandong province, China was taken as a case area, which was classified and graded in this research considering selenium, nutrients and environmental quality in soils. Zone I and II are suitable to develop selenium-rich agriculture, which accounts for 37.2% of the total area in Boshan. Zone III can develop selenium-rich agriculture by adding fertilizer of selenium into farmlands. Zone V accounted for 1.89 km², and it is forbidden to develop agriculture due to pollution in soils exceeding the criteria. The heavy metal Cd, PAHs, HCHs and DDTs in fractions are significant responsible pollutants of Boshan. These pollutants remained in soils, which may have been caused by the abuse of pesticides and industrial pollution in the past. This assessment for selenium resources in the case area was expected to provide the basis for selenium-rich agriculture and also for regional planning of Boshan.

Taking comprehensive consideration of selenium resources, soil nutrient and environmental quality, the comprehensive assessment system of regional selenium resource was established based on analytic hierarchy process, which was expected to provide scientific support for the development of local agriculture. This study provides an example of the evaluation of regional selenium resources, although the methods and criteria for assessing selenium resources still need to be further investigated and refined.

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Fig. 5. Comprehensive assessment of regional selenium resources in Boshan. (I–V represent different grades of the comprehensive assessment).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.scitotenv.2017.06.150>.

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