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Original Research

Spatial Distribution and its Driving Forces Analysis of Soil Heavy Metals in Semi-Arid Grassland Surface Coal Mining Areas

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Abstract

For thousands of years, the development and utilization of coal have significantly contributed to human progress; however, they have also engendered a series of ecological, social, economic, and environmental problems, such as Soil Heavy Metal (SHM) pollution. At present, there is a lack of large-scale investigations, systematic sampling, spatial distribution, and driving force analyses specific to SHM contamination in semi-arid grassland surface coal mining groups. The existing studies cannot fully grasp the distribution characteristics of soil heavy metal pollution within these mining clusters, let alone the hazards posed by surface coal mining to surrounding farmland and pastureland. Given this, this study focuses on the Shengli Coal Field in Xilinhot City, situated in the heart of the Xilingole Grassland, as a case study to examine the spatial distribution (SD) and driving forces of SHM in semi-arid grassland surface coal mining areas. The key findings are as follows: (1) The spatial distribution patterns reveal that *As* is primarily concentrated in the southern regions of the surface germanium mine and the western area of the No. 2 surface mine. *Cd* was mainly distributed in the grassland and waste dump in the northwest of the No. 1 surface mine. *Cu* was mainly distributed in the northwest and northeast of the study area. The SD of *Zn* was relatively similar to that of *Cu*. *Pb* is mainly distributed in the grassland and waste dump in the northwest of the No.1 surface mine. *Se* was mainly distributed in the north of the west at No. 2 and No. 3 surface mines. *Ge* was mainly distributed in the surface germanium mine and its surrounding areas. *Cd* is mainly present in the grassland and waste dumps located in the northwest of the No. 1 surface mine. *Cu* exhibits a prominent distribution in the northwest and northeast of the study area, while the SD of *Zn* is relatively similar to that of *Cu*. *Pb* is predominantly found in the grassland and waste dumps northwest of the No. 1 surface mine. *Se* is concentrated in the northern regions of the west No. 2 and No. 3 surface mines. *Ge* is primarily distributed within the surface germanium mine and its vicinity. (2) The driving factors influencing

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the SD of SHM in the study area encompass vegetation cover, water resources, surface mining, urbanization, agriculture, and industrial activities. These factors interact and contribute to the observed spatial patterns of SHM contamination. This study provides a scientific foundation for assessing and restoring the soil environment in semi-arid steppe surface coal mining areas. Furthermore, it offers valuable insights and serves as a reference for ecological restoration efforts and planning initiatives aimed at mitigating the environmental impacts of surface coal mining in these fragile ecosystems.

Keywords: soil heavy metals, surface coal mine areas, spatial distribution, driving forces, semi-arid grassland

Introduction

Coal is one of the most vital basic energy sources and chemical raw materials for mankind and has a prominent strategic position in global economic development. According to the statistical data of the BP Statistical Review of World Energy 2021|70th Edition, coal was the second largest fuel in the world in 2020, accounting for 27.2% of the total primary energy consumption. China's proven coal reserves are 143.197 billion tons, accounting for 13.3% of the world's total, ranking fourth in the world. Despite the challenges posed by factors such as the COVID-19 pandemic and imbalances in international energy supply and demand, China's coal production in 2020 reached 4.13 billion tons, accounting for 50.7% of the world's total, ranking first in the world and hitting a record high. Similarly, China's coal consumption accounted for 55.5% of the world's total in 2020, also ranking first globally. Within China, coal played a pivotal role in primary energy consumption, contributing 55.58% of the total primary energy consumption in the Chinese Mainland. Furthermore, coal-fired power generation accounted for 63.22% of China's total electricity production in 2020, underscoring the indisputable status of China's coal industry in both the domestic and international energy industries.

Although the development of coal resources is crucial to socio-economic development, some adverse impacts of coal development on the natural ecosystem and environment are inevitable, as potential toxic substances can be discharged into the soil, atmosphere, and water [1, 2]. Xin Dong et al. have revealed that, in comparison to background values, the concentrations of *Cd*, *Hg*, *Cu*, *Pb*, *Zn*, *As*, *Ni*, and *Cr* in soils surrounding mining areas in China have escalated by 820.7%, 309.6%, 158.6%, 158.6%, 146.0%, 103.4%, 24.6%, and 15%, respectively, with Cd and Hg exhibiting the most significant increases [3]. The large-scale development and utilization of coal in surface mining areas is generally considered to be the main factor affecting the content of heavy metals in topsoil, and further causing a series of important issues such as serious regional ecological damage, land degradation, and environmental pollution [4]. Increasing evidence also indicates that Soil Heavy Metal (SHM) pollution has become one of the most serious ecological and environmental issues in the world due to human activities such as rapid industrialization and urbanization [5]. Pollution of the natural environment by heavy metals is a worldwide problem because these metals are indestructible and most are toxic to living organisms at certain concentrations. Soil Heavy Metals (SHM) have distinct properties such as recalcitrance to decomposition, concealment, long-term stability, and proneness to accumulation. They infiltrate the food chain via diverse pathways, posing direct or indirect threats to human health and safety. The risks associated with SHM exposure vary significantly across life stages and populations, with variability, dynamics, and randomness characterizing the entire process of health risk transmission from soil contamination [6]. SHM has increasingly become a major research focus with high attention. Exposure to heavy metals in the human body can elicit deleterious effects on vital organs such as the kidneys, liver, lungs, and eyes, as well as critical biological systems including the nervous, reproductive, immune, and respiratory systems, leading to diseases such as anemia, nausea, cancer, bone mineral loss, organ failure, and tumor induction [7]. Soil, as a pivotal environmental medium, operates within an open and receptive system. Thus, the accumulation of heavy metals has become increasingly prominent, and it has shown an upward trend from local to regional spread, from slow accumulation to rapid outbreak [8]. Soil is a spatiotemporal continuous variant. Due to the spatial continuity of natural landscapes, soil formation processes, and climatic zones, soil properties are not spatially independent and uniform from each other, as assumed by Fisher's principle, but correlated with each other within a given area. Different pollution sources lead to complex spatial heterogeneity of SHM [9, 10]. Therefore, in-depth research on the Spatial Distribution (SD) characteristics and driving forces of SHM pollution in coal mining areas is the basis for studying the migration laws of SHM, soil environmental quality assessment, and the impact of coal development on the ecological environment. It can provide a theoretical basis and guidance for preventing and controlling heavy metal pollution in coal mines and surrounding soil, improving the ecological environment, formulating ecological restoration policies for mines, and rationally utilizing land resources. In recent years, many scholars have carried out numerous studies on the SD of SHM pollution in coal mine areas. Multivariate statistical analyses, cluster analyses, and principal component of the research of Mohammad A. H. Bhuiyan et al. [4] showed that *Mn*, *Pb*, *Zn,* and *Ti* are derived from anthropogenic activities, particularly coal mining activities in the northern part of Bangladesh. Yonghong Zhang et al. [11] research results show that through the analysis of enrichment factors, the soil in the reclamation area of Huainan Panyi Coal Mine was affected by coal mining and coal gangue dumping. S. K. Reza et al. [12] research showed that SHM of surrounding agricultural fields was affected by mine drainage of the Ledo coal mining area in Tinsukia district, Assam, India. Jing Li et al. [13] applied the Nemero index method, geological accumulation index method, and potential ecological hazard index method to evaluate the level of heavy metal pollution in soil and potential ecological hazards. The results of the study indicate that the SHM content within 4 km of the mining site in Baorixile, Inner Mongolia, China, was generally free of contamination. Fang Li et al. [14] used the single factor pollution index method, the Nemero pollution index method, and the ground accumulation index method to study a coal mine in the southwest of Shandong Province, China. The results of the study show that the six heavy metal elements have accumulated significantly in the surrounding areas, such as gangue hills, industrial plazas, coal transfer stations, and transport routes, with different SD characteristics. Y. Y. Yang investigated the concentrations and speciation of As, Cu, Cd, Zn, Pb, and Cr in the topsoil of an overlapped area of farmland and coal resources in Xuzhou, China. The results showed that the mean concentrations of all six metals were higher than the background values of Xuzhou [15]. Di Liu et al. research results showed that the contents of Cu, Cr, Ni, As, Zn, Cd, Pb, and Hg were greater than the background values of soil elements in Shanxi Province, and the Cd and Pb contents around the coal preparation plants were the highest [16]. Yongkang Zhang et al. used the single factor index method and potential ecological hazard index method to analyze heavy metal pollution and its potential ecological hazard risk in an abandoned coal mine area [17]. Pengwei Qiao et al. research shows that zones with a high concentration of heavy metals were closer to the road and farther from the mine area, which had low NDVI, a large slope, high terrain, and large PH values [18]. Yuqi Zhang et al. applied soil contamination risk indexes, a positive matrix factorization model, a Monte Carlo simulation, and a human health risk analysis model to investigate the risk of SHMs in a typical mining town in North China [19]. Haijian Xie et al. used positive matrix factorization and Monte Carlo simulation to evaluate the ecological and human health risks of SHMs in mining-affected areas [20]. Xiaojing Zhang et al. clarified the effects both of mining and land use types on the spatial distribution and particular sources of SHMs using inverse distance weighted and the positive matrix factorization model [21]. Fuling Zhang et al. used principal component analysis, positive matrix factorization models, and geostatistical analysis to investigate the source of SHMs in a Plateau Alpine Mining Area [22]. Shijie Song et al. used the nemerow integrated pollution index, potential ecological risk index, and human health risk assessment model to evaluate the pollution and risk of heavy metals (Cu, Cr, As, and Pb) in the soil around the typical coal gangue hill in the Fengfeng mining area of China [23].

Despite extensive research conducted by scholars from various nations on SHM contamination in mining areas, the current studies primarily focus on industrial plazas of coal mines or within mine perimeters, featuring narrow research scopes and limited sampling points. A significant gap remains in large-scale investigations, extensive sampling, spatial distribution (SD) analysis, and driving force studies specifically targeting surface coal mine groups located in semi-arid grassland regions. Therefore, it is challenging to comprehend the global distribution patterns of SHM pollution in such surface coal mine clusters, and it is even more difficult to grasp the heavy metal pollution hazards caused by surface coal mining on surrounding farmland and pastures, especially the relevant research on SHM from surface coal mines in ecologically fragile areas such as semi-arid grasslands. In light of these limitations, this study aims to: (1) Determine the concentrations of heavy metals (*As*, *Cd*, *Cu*, *Ge*, *Pb*, *Se*, and *Zn*) in the soil of Shengli Coalfield and its adjacent areas in Xilinhot City, Inner Mongolia Autonomous Region, China. (2) Analyze the spatial distribution (SD) characteristics of SHM in semi-arid grassland surface coal mining areas. (3) Analyze the driving forces that shape the spatial distribution of SHM originating from surface coal mining activities in semi-arid grassland regions.

Materials and Methods

Study Area

The study area is located in the Shengli Coal Field in the northern suburb of Xilinhot City, Inner Mongolia Autonomous Region, China. The geographical coordinate range of the research area is 43°51′46″~44°9′6″ N, 115°49′53″~116°18′23″E (Fig. 1). The planned area of Shengli Coal Field is about 423 square kilometers, with a total coal resource of about 22.4 billion tons. It is currently the thickest coal seam and largest reserve lignite coal field in China and is one of China's largest national coal bases. The climate of the study area belongs to the temperate and semi-arid continental westerlies, with significant characteristics such as aridity, low temperatures, windiness, lengthy periods of sunshine, significant temperature variations, a brief frost-free season, scarce precipitation, low air humidity, high wind speeds, and substantial evaporation rates.

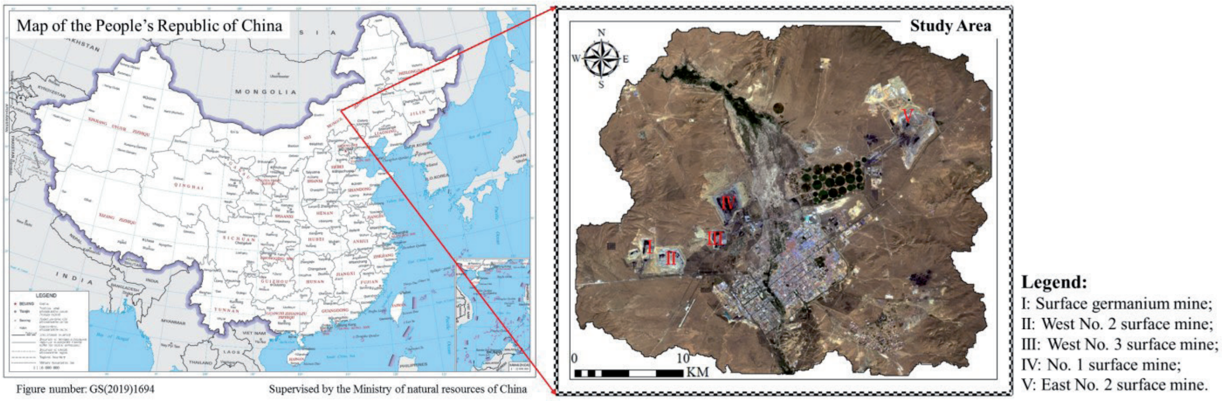


Fig. 1. Location of the study area.

Data Source and Processing

The Digital Elevation Model (DEM) was acquired from the Geographic Information Monitoring Cloud Platform (http://www.dsac.cn/). The July 2017 Landsat OLI imagery, with the data identifier LC81240292017198LGN00, was downloaded from the United States Geological Survey (USGS) website. Pre-processing of the Landsat OLI imagery was conducted using ENVI 5.1 software, encompassing radiometric correction, FLAASH atmospheric correction, geometric correction, and image cropping. The band operation method was used to calculate the Normalized Difference Vegetation Index (NDVI) (Equation 1). The landscape ecological classification system and corresponding data for the study area in 2017 were adopted from existing research findings [24, 25]. The distances to the nearest town landscape, agricultural landscape, industrial and storage landscape, mining landscape, road network landscape, and water landscape were obtained using the Euclidean distance method within ArcGIS spatial analysis (Fig. 2) [24]. The slope and aspect parameters were derived from the DEM using Topographic Modeling in ENVI.

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}} \tag{1}$$

Where ρ_{Red} represents the red band, ρ_{NIR} represents the near infrared red band;

Collection and Testing of Soil Samples

In this study, soil samples were collected between July and August 2017. A grid-based approach was employed to preliminarily arrange sample points, with a grid size of 1 km × 1 km. During the actual sampling process, considering the land use patterns and soil environmental characteristics specific to the Shengli

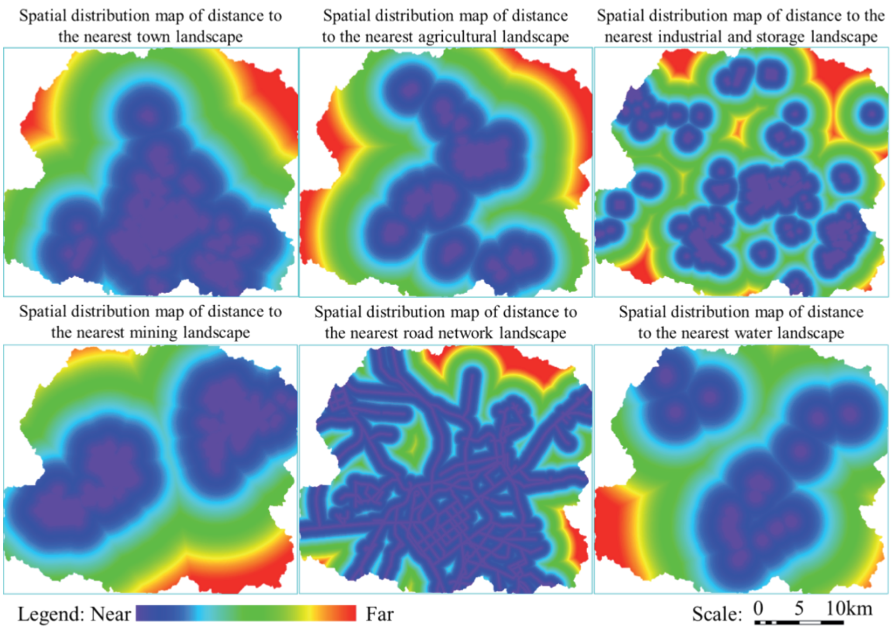


Fig. 2. Spatial distribution map of distance to the nearest landscapes [24].

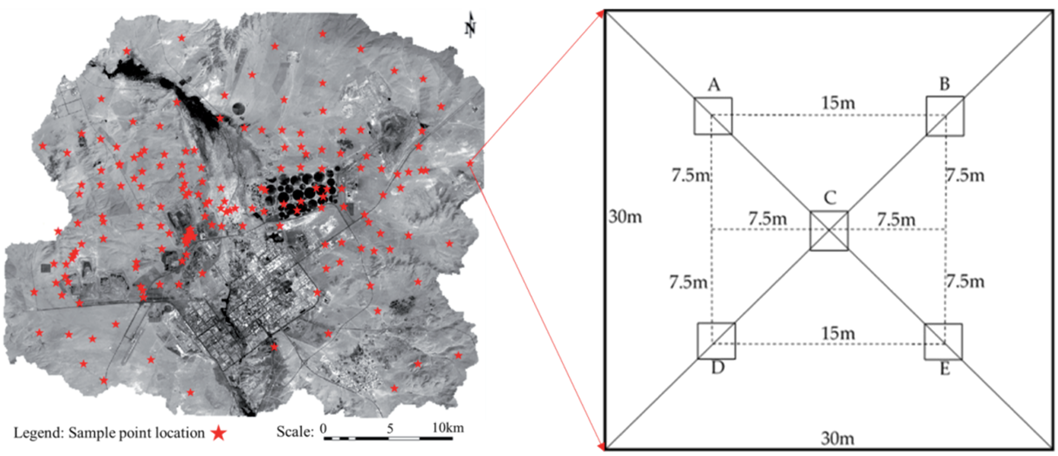
coalfield, sampling was conducted at representative locations within the grid that effectively mirrored the region's environmental quality. Areas with identified pollution sources underwent more intensive sampling, resulting in a total of 152 sample points (Fig. 3a). The sampling depth was standardized at 0-20 cm. To align with the Landsat data utilized in this study, the sample size was designated as 30 m × 30 m, where each sample comprised a composite of the central point and four surrounding subsamples (Fig. 3b). A dedicated soil sampler was employed for collection, with each sampling point yielding 1.0kg of soil. The Galaxy 1 RTK survey system facilitated positioning, and the collected soil samples were placed in labeled polythene bags, accompanied by site photographs. The soil samples were then stored in a dust-free, ventilated, and dark environment for natural air drying. Subsequently, debris such as stones, plant roots, and leaves were removed, and the soil was carefully ground and passed through a 120-mesh sieve. The sieved soil was thoroughly mixed and stored in paper bags prior to testing. The concentrations of *As* and Se were determined using the hydride-atomic fluorescence spectrometry method, while *Ge* was measured via flame atomic absorption spectrophotometry. *Pb*, *Cd*, *Cu*, and *Zn* were quantified using atomic absorption spectrophotometry.

Making of SD Map of SHM

The outliers in the study data were identified using the mean ±3 standard deviations criterion. Data outside this range were labeled as abnormal values, and the maximum and minimum values of normal data were used to replace the specific values, respectively. Descriptive statistical analysis, Kolmogorov-Smirnov (K-S) tests, and one-way analysis of variance (ANOVA) were performed on the sample data using SPSS 24.0 software. Based on the software Canoco 4.5, a typical correspondence analysis was conducted between terrain factors and soil nutrients. Semi-variogram analysis and theoretical model fitting were performed using geo-statistical software GS+9.0. Conduct trend effect analysis, Kriging interpolation, cross validation, and map editing on the ArcGIS 10.4 platform to produce SD maps of SHM. Statistic the maximum and minimum values of the SD map of SHM, and use the statistical values to normalize the data [26].

Analysis Method for Driving Forces of SD of SHM of the Surface Coal Mining Area

Understanding the driving forces of the spatial distribution of soil heavy metals is essential for effective risk management [27]. Dynamic changes in SHM are mainly driven by natural and human factors. Because the scope of our study area is relatively small, the differences in natural driving forces (e.g., climate, soil, plant diversity, etc.) are small as well. At the same time, our study area is located at the northern border of China, which is an area populated by Mongolians. Their population growth is very slow, and their cultural concepts are very similar. Progress and development in science, technology, the economy, and other aspects are relatively slow as well. Based on the characteristics of the study area and the needs of this study, this study selected elevation, slope, aspect, vegetation (NDVI), and distance to the nearest water landscape as natural driving factors, and selected the distance to the nearest mining landscape, the town landscape, the industrial and storage landscape, the agricultural landscape, and the road network landscape as human driving factors [28, 29]. Geographical detectors reveal the driving force behind the SD characteristics of dependent variables by exploring the degree to which independent variables explain dependent variables. As a tool for detecting and utilizing spatial differentiation, the geographical detector has the greatest advantage that it does not have too many assumptions and can effectively overcome the limitations of traditional statistical methods. It has been widely used in the field of natural and social research.



(a) Spatial distribution of sample plots (b) Layout of quadrat

Fig. 3. SD of soil sample plots and layout of quadrat.

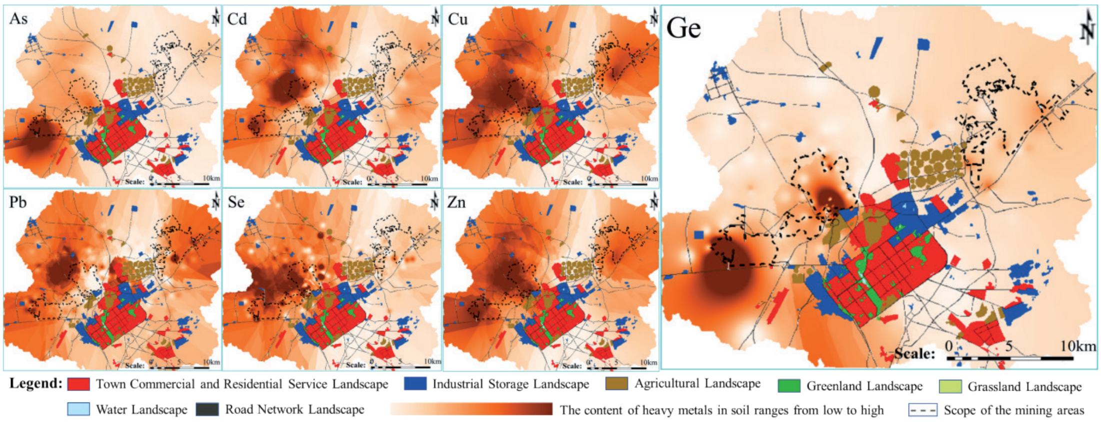


Fig. 4. SD map of SHM in the study area.

In this study, geographical detectors were selected as the primary analytical tool to measure and analyze the driving forces influencing the SD of SHM in surface coal mining areas:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \tag{2}$$

Where q represents the interpretation rate of the influencing factor, with a value range of 0 to 1. The larger the q value, the stronger the interpretation rate. The X and Y variables are superimposed in the Y direction to form an L layer, represented by h = 1, 2, 3,..., L. N_h and N are the sample numbers of the sub region h and the entire region, respectively. σ_h^2 and σ^2 is the discrete variance of the sub region h and the entire region Y, respectively [30, 31].

Results

SD of SHM in the Surface Coal Mining Area

As this study focuses on the evaluation of the SD of SHM in semi-arid grassland surface coal mining areas, only mining landscapes and grassland landscapes were retained in the evaluation of the SD of SHM. As shown in Fig. 4, the difference of the ordinary Kriging exponential function for *As* has the best effect. The areas with the highest *As* content are distributed in the surface germanium mine, west No. 2 surface mine, and its southern grasslands. The No.1 surface mine and its northwestern grasslands also have higher *As* content, while other areas have lower and more uniform *As* content. *Cd* adopts an exponential function variation model. The areas with the highest *Cd* content are distributed in the grasslands and waste dumps northwest of the No.1 surface mine. The surface germanium mine and its surrounding areas also have high *Cd* content, and the *Cd* content in the northwest of the research area is significantly higher than that in other areas. *Cu* is mainly distributed in the northwest and northeast of the study area, especially in the grassland and waste dump in the northwest direction of the No.1 surface mine. The *Cu* content in the pit and surrounding areas of the East No. 2 surface mine is also high. It is worth noting that the SD of *Zn* is relatively similar to that of *Cu*. The best interpolation effect is achieved by using spherical functions for *Pb*. The area with the highest *Pb* content is the grassland and waste dump in the northwest direction of the No.1 surface mine. *Pb* content in the western, northwestern, and northeastern steppes of the study area is relatively high. *Se* adopts the ordinary Kriging exponential function for interpolation. *Se* is mainly distributed in the north of the west No. 2 surface mine and the west No. 3 surface mine. The *Se* content in the No. 1 surface mine and its surrounding areas is also relatively high. The Se content in the west of the study area is significantly higher than that in the east. *Ge* adopts an exponential function variation model for interpolation. Undoubtedly, the area with the most *Ge* distribution is in the surface germanium mine and its surrounding areas. The *Ge* content in the grasslands on the south and southeast sides of the surface germanium mine is significantly higher than that in other grassland areas. The *Ge* content in the No. 1 surface mine is also relatively high.

Driving Forces Analysis of the SD of SHM

As can be seen from Table 1, q values of NDVI and distance to the nearest water landscape exceeded 0.85 for all seven heavy metals. This indicates that NDVI and water landscape have a strong driving effect on the SD of SHM in the study area. The distance to the nearest mining landscape, the distance to the nearest town landscape, the nearest industrial and storage landscape, and the nearest agricultural landscape all have q-values above 0.6. This indicates that these four drivers also have a clear driving effect on the SD of SHM in the study area. Distance to the nearest road network landscape, elevation, slope, and aspect have q

Table 1. *q* values of driving factors of SD of SHM in the study area.

	As	*Cd*	*Cu*	*Ge*	*Pb*	*Se*	*Zn*
Town	0.8671	0.9186	0.8869	0.8444	0.7006	0.8465	0.8870
Agriculture	0.9114	0.8944	0.8601	0.8927	0.8465	0.8638	0.8602
Industry	0.7428	0.7113	0.6953	0.7074	0.6130	0.7007	0.6974
Mine	0.7202	0.7720	0.8659	0.6376	0.7912	0.7515	0.8485
Road	0.3595	0.4013	0.3769	0.3435	0.3446	0.3799	0.3727
Water	0.9736	0.9120	0.9146	0.9701	0.8589	0.9380	0.9177
Altitude	0.1188	0.1818	0.1618	0.1118	0.1654	0.1457	0.1456
Aspect	0.0193	0.0186	0.0190	0.0067	0.0069	0.0280	0.0197
Slope	0.0086	0.0008	0.0025	0.0098	0.0002	0.0077	0.0026
NDVI	0.9973	0.9931	0.9960	0.9984	0.9945	0.9960	0.9960

values less than 0.4. This indicates that the driving effect of these four driving factors on the SD of SHM in the study area is not significant.

Discussion

Effects of Vegetation, Water, Town, Agriculture, Industry, and Surface Mines on SHM

According to the average *q* value over the years, the primary driving factors affecting the SD of SHM of the study area include vegetation, water, surface mines, town, agriculture, and industry. As an important component of terrestrial ecosystems, plants play a key role in the biogeochemical cycle of heavy metals [32]. Vegetation can effectively intercept, absorb, and transform SHM in the air [33-36]. Plant cover can also effectively resist rainfall and runoff erosion, determine the loss of SHM, hinder the migration of SHM to surrounding water, and thereby have an impact on the SD of SHM [37, 38]. Rainfall runoff is an important factor affecting the movement of heavy metals and is also the source of non-point source heavy metal pollution in large areas of surface water. Watershed pollution with heavy metals arises from soil erosion and subsequent migration and diffusion through river systems [39]. Industrial pollutants, construction materials, asphalt pavements, vehicle exhaust, urban rainwater and sewage, and household garbage are all important sources of heavy metal pollution in cities [40]. High-intensity input of agricultural chemicals such as fertilizers and pesticides is an important cause of heavy metal pollution in large areas of farmland and its surrounding areas, especially in farmland irrigated with wastewater, which can lead to serious heavy metal pollution in farmland and their surrounding areas [41]. Different industrial sectors have significant impacts on the environmental pollution of heavy metals [42], such as: *Cd* comes from the paint industry, the electroplating industry, batteries, dyes, electronic waste, and nuclear power plants [43]. *Pb* mainly comes from paint, pigment, metallurgy, glass industry, etc. *Zn* comes from the smelting, galvanizing, dye, oil refining, and fertilizer industries [44]. *Cu* mainly comes from industries such as smelting and copper product production. The sources of *As* include pigment, papermaking, pesticides, sulfuric acid, chemical fertilizer, textiles, metal, glass, leather, medicine, ammunition, and other industries. *Se* is sourced from metallurgy, glass, ceramics, electronics, solar, feed, and other industries. *Ge* comes from semiconductor, aerospace, nuclear physics, optical fiber communication, infrared optics, solar energy, chemical biomedical, and other industries.

This paper focuses on the impact of surface coal mining on SHM. During the development of surface coal mines, coal mining, coal transportation, coal processing, coal storage, tailings accumulation, mine water drainage, and dust emission may cause heavy metal pollution to the surrounding soil [45], which in turn poses a huge challenge to the ecological safety of urban dwellers and agriculture and animal husbandry [46-48]. According to the survey results of the National Soil Pollution Survey Bulletin jointly released by the Ministry of Ecology and Environment of China and the Ministry of Land and Resources of China in 2014, the overall exceedance rate of soil in China was 16.1%, and of the 1,672 soil sites in 70 mining areas surveyed, 33.4% exceeded the standard, with cadmium, lead, and arsenic as the main pollutants [49]. The SHM mainly comes from the heavy metals in ore symbionts and associated minerals [50]. They enter the soil environment in and around the mine site during the mining and transport chain, where they are continuously enriched [51]. Heavy metal pollution occurs when SHM environments are enriched to a certain extent. The enrichment of SHM can destroy the physical, chemical, and biological properties of soil, causing irreversible pollution to the ecosystems and environment [52], and with the continuous progress of production activities, heavy metals will migrate in the form of dust particles and enter the surface soil in the form of dry and wet sedimentation, resulting in more severe heavy metal migration [44]. Surface coal mining produces a large amount of solid waste containing heavy metal ions, which can enter the soil surface under the invasion and scouring of rainwater, causing surface SHM pollution [53]. Surface soil may migrate under the influence of wind or surface runoff, resulting in the accumulation of SHM pollution in areas surrounding mining sites [42, 54].

Hazards of SHM to Human Beings

Assessing the harm of SHM pollution to humans is an important prerequisite for soil environmental risk management. Soil, as a crucial environmental medium, operates within an open and inclusive system. The accumulation of heavy metals has become increasingly prominent, and it has shown an upward trend from local to regional spread, from slow accumulation to rapid outbreak [55]. Given the enormous pressure on human health and food safety, how to accurately and deeply identify the harm caused by SHM pollution to human health and then strengthen accurate and effective risk management and control of SHM pollution is particularly crucial. Soil quality in grassland areas has a direct or indirect impact on the production and livelihood of pastoralists [56]. Heavy metals can affect the quality of livestock products and human health through migration and long-term exposure [57]. *Cu* and *Zn* are essential elements for the human body, yet their excessive intake can lead to adverse health effects. Excessive absorption of *Cu* by the human body can cause hypotension, black stool, hematemesis, coma, jaundice, gastrointestinal discomfort, vomiting, nausea, respiratory problems, abdominal pain, and liver and kidney failure. Prolonged exposure to a large amount of *Zn* in the human body can cause significant decreases in blood copper concentration, abdominal pain, anemia, vomiting, hypertension, coronary heart disease, leukopenia, impaired immunity, and reduced bone weight [58]. Excessive absorption of *Cd* by the human body can cause kidney failure, emphysema, osteoporosis, pain disorders, endocrine disorders, and anemia. *As* is also known as arsenic. Chronic *As* poisoning mainly manifests as vomiting, numbness, diarrhea, muscle cramps, skin diseases, neurological weakness, digestive disorders, etc. Long-term exposure to *As* is associated with an increased risk of skin cancer, bladder cancer, lung cancer, etc. [43, 59]. *Pb* has toxic effects on the human nervous system, blood, and vascular system. Its early symptoms are cytopathic changes, which can lead to anemia, hypertension, reproductive ability, and decreased intelligence after chronic poisoning. *Se* plays an important role in cellular aging resistance, immune system enhancement, and cancer prevention. Severe selenium deficiency is the main cause of two endemic diseases: Keshan disease and Kashin-Beck disease [60]. However, excessive intake of *Se* can lead to poisoning symptoms such as dry and brittle hair prone to shedding, fragile nails with white spots and longitudinal lines, skin damage, muscle spasms, neurological abnormalities, and in extreme cases, death. *Ge* is a trace element with a variety of biological activities, which has a wide range of preventive and therapeutic effects on the human body and has functions such as promoting blood circulation, anti-tumor, anti-inflammatory, antiviral, and improving immunity. *Ge* has been described by scientists as the "life-saving germanium of the 21st century" and the "miracle element of life" [61]. Excessive *Ge* can also cause poisoning, with symptoms such as weakness, anemia, vomiting, arrhythmia, and nephritis.

Suggestions for the Remediation of SHM in Semi-Arid Steppe Surface Coal Mining Areas

Soil heavy metal pollution caused by mining in mining areas seriously affects crop yield and causes human diseases. It is necessary to prevent soil heavy metal pollution from damaging health [62]. On 28 May 2016, the State Council of the People's Republic of China issued the Action Plan for the Prevention and Control of Soil Pollution, which proposes ten major 35 measures to prevent and control soil pollution, focusing on strengthening environmental supervision of unused land in areas affected by mining, oil fields, and other mineral resource exploitation activities, and promptly urging relevant enterprises to take preventive and control measures if soil pollution problems are found. With the increasing attention paid to heavy metal pollution, coal mining areas as high-risk areas have attracted widespread attention from scholars to the remediation of SHM in mining areas. Methods that can be used to remediate SHM in mining areas include physical remediation (Electrokinetic remediation, sorting, thermal desorption, et al.), chemical remediation (Chemical precipitation, floatation, complexation, distillation, et al.), bioremediation techniques (protozoa, worms, insects, et al.), adsorption techniques (available adsorbents include microorganisms, fungi, bacteria, algae, industrial waste, clay, peat, nanomaterials, et al.), and combined remediation techniques (plant microbial combined remediation technology, combined bone char-zeolite remediation technology, bio-electrochemical remediation technology) [43].

In addition to specific remediation techniques, this study believes that the construction of landscape patterns can also be used to deal with the pollution and diffusion of SHM in semi-arid grassland surface coal mining areas. (1) Using vegetation buffer zones to block, absorb, and transform SHM pollution diffusion [33]. (2) Utilize natural and constructed wetlands to precipitate, degrade, or absorb heavy metals through aquatic organisms. (3) Vegetation and water are used to provide spatial isolation from mining disturbances [33]. Vegetation buffers can be established in areas (usually strips) covered by suitable vegetation or wetlands between the mine site and the grassland, whose main function is to remove heavy metals in transit [63]. Constructed wetlands are not only suitable for point source pollutants, but also effective methods for removing various heavy metals from surface runoff. Therefore, ecological corridors and constructed wetlands can be constructed to block, absorb, or degrade the diffusion of heavy metals in surface coal mining areas.

Limitations and Uncertainties

A total of 152 samples were collected and tested in this study. If more samples were collected, more accurate results of SD of SHM would be obtained. The research area is a regional complex embedded by various ecosystems such as industry (including thermal power plants, cement plants, etc.), agriculture, animal husbandry, mining (including coal, petroleum, germanium, etc.), and town. In this study, the driving force of SD of SHM was analyzed only by using the method of geographic detector, and the influence mechanism of various natural and human factors on SD of SHM was not deeply studied. However, these limitations and uncertainties are not large enough to affect the general results of this study.

Conclusion

This study took the Shengli Coal Field in Xilinhot City, the hinterland of Xilingol Grassland, as an example to study the SD and driving forces of SHM in the semi-arid grassland surface coal mining areas. The results showed that: (1) *As* is mainly distributed in the surface germanium mine, the west No. 2 surface mine, and their southern grassland. *Cd* is mainly distributed in the grassland and waste dump in the northwest direction of the No.1 surface mine. *Cu* is mainly distributed in the northwest and northeast of the study area. The SD of *Zn* is relatively similar to that of *Cu*. *Pb* is mainly distributed in the grassland and waste dump in the northwest direction of the No. 1 surface mine. *Se* is mainly distributed in the north of the West No. 2 surface mine and the West No. 3 surface mine. *Ge* is mainly distributed in surface germanium mines and their surrounding areas. (2) The driving factors affecting the SD of SHM of the study area include vegetation, water, surface mines, town, agriculture, and industry. At the same time, this study also discussed the impact of vegetation, water, surface mines, towns, agriculture, and industry on SHM, analyzed the harm of SHM to humans, and proposed suggestions for the remediation of SHM in the semi-arid grassland surface coal mining areas.

Conflict of Interest

The authors declare no conflict of interest.

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Author Contribution

Zhenhua Wu constructed the review. Xiaoying Wang collected the literature and helped in the drafting of the manuscript. Zhenhua Wu wrote and revised the manuscript. Ziqiang Dai advised and supervised the project. Qiao Yu provided funding.

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