



Surface coal mining impacts on land use change and ecological service value: a case study in Shengli coalfield, Inner Mongolia

Lijia Zhang^{1,2} · Xu Zhou² · Yan Zhou² · Ji Zhou² · Jiwang Guo³ · Zihan Zhai² · Yan Chen² · Xiangyan Su² · Lingxiao Ying⁴ · Liwei Wang² · Ying Qiao²

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Abstract

Coal plays a crucial role in global economic development and remains the most common and widely distributed fossil fuel worldwide. As the world's largest developing country, China's mining and utilization of coal resources have contributed significantly to the country's rapid economic growth. Inner Mongolia is an ecologically fragile arid and semi-arid area of China. The exploitation of opencast mining has seriously hindered the sustainable use of regional land and the residents' well-being. Using ENVI-based remote sensing images from 2000, 2005, 2010, 2015, and 2020, this study employed a random forest algorithm to divide land utilization types into construction land, vegetation, cultivated land, bare land, and water areas and analyzed the characteristics of land use and ecosystem service value changes over the past 20 years. The results were as follows: (1) Construction land in the mining area changed minimally from 2000 to 2020; vegetation and water bodies showed a decreasing trend, whereas bare and cultivated lands showed an increasing trend. Bare land exhibited the largest change in area proportion and water bodies the smallest. (2) The total ecosystem service value of the mining area declined from 10.939 to 9.527 billion Yuan. Vegetation ecosystem service value was the highest, followed by cultivated land and water, with the bare land ecosystem service value the lowest. (3) On a spatial scale, the total ecosystem service value of the Shengli mining area decreased year by year, indicating that land use changes in the mining area do have an impact on ecosystem service value.

Keywords ESV · Land use change · Transformed matrix · Spatial and temporal change

1 Introduction

Coal plays a crucial role in global economic development and remains the most common and widely used fossil fuel in the world. As the world's largest developing country, China's mining and utilization of coal resources have contributed significantly to the country's rapid economic growth (Zhu 1999). China's economy will continue to depend heavily on coal mining and production in the future (Bi et al. 2019;

Wang 2014; Lin et al. 2014). Despite promoting economic development, high-intensity coal mining inevitably causes land use and ecosystems disturbances (Holdren and Ehrlich 1974; Xiao et al. 2020a, b). Opencast mining destroys the ecological environment of the mine (Mukhopadhyay et al. 2016) by removing vegetation and soil, altering the terrain, and disturbing surface and below-ground hydrological systems. Therefore, it is necessary to monitor and study the impact of mining on ecosystem functions, especially in the Shengli field of Inner Mongolia, which is an ecologically fragile area (Abernethy et al. 1999; Westman et al. 1997). The success of mining operations in the Shengli coalfield has caused a certain degree of damage to the regional ecosystem, resulting in a series of ecological and environmental issues that have caused wide-ranging concerns across society.

Ecosystem services refer to various benefits that humans obtain directly or indirectly from ecosystems (Costanza et al. 1997). In the past 20 years, ecosystem services have developed rapidly, such that they meet human needs and

✉ Xu Zhou
twz202109@163.com

¹ China University of Mining and Technology, Beijing 100083, China

² Land Consolidation and Rehabilitation Center, Ministry of Natural Resources, Beijing 100035, China

³ Zhejiang University, Zhejiang 310007, China

⁴ State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

well-being and impact society (Wohlfart et al. 2017; Smith et al. 2013), which is the basis of human survival and development (Li et al. 2013; Peng 2021). Ma (2005) divided the ecosystem into supply services, support services, regulation services, and cultural services (Liu et al. 2014). The MA (The Millennium Ecosystem Assessment) evaluation process and scholarship of many researchers have divided the ecosystem service types into supply services, adjustment services, and cultural services (Zhou et al. 2021). Costanza et al. (1997) and Daily assessed the global ecosystem service value and provided methods and cases for ecosystem service value calculations. In 2003, Xie et al. (2003) organized the "China's land ecosystem area ecological service value ecosystem", following the status quo of China's land use status, according to the China Land Use Status (Dai et al. 2020). This laid the foundation for scientifically quantifying ecosystem service values in different regions (Xie et al. 2003). The ecosystem service assessment method is divided into three primary categories: energy value analysis, material assessment methods, and value quantity assessment methods (Paudel et al. 2012; Wu et al. 2012; Zhao et al. 2000). Most current related research in China is based on the ecosystem service value equivalent factor table, which was revised and supplemented by Xie and combined with the economic value of the study area ecosystem services to estimate regional ecosystem service values (Li et al. 2018; Xie et al. 2015).

With the increases in population growth and technology, the demand for ecosystem services has increased, and human activities have also become one of the main factors affecting ecosystem services (Huang 2000; Maltitz et al. 2016). Land use changes are the most direct form of human activity affecting the Earth's surface system and play an important role in global environmental changes (Liu et al. 2011). Studying the ecosystem service value of specific regions based on various land use characteristics has great significance for revealing the impact of human activities on the ecosystem and the relationship between coordinators and nature (David 1971; Ren et al. 2019). Through analyses of how land use changes affect the value of ecosystem services, many scholars have revealed the negative impact of trends such as urbanization, which has a negative impact on ecosystem service value (Cao et al. 2007; Kai 2000; Olsen et al. 2007). A number of studies have preliminarily explored the underlying causes of impacts and suggested that future land use decisions require additional consideration of ecological environment impact (Zhang et al. 2013; Xiao et al. 2020a, b). Related research showed that changes in land use modification and ecosystem service values have strong relevance to agricultural development and urbanization; changes in land use modes often lead to a decline in regional ecosystem services, suggesting that the ecological environmental effects of land use practices should be taken into consideration (Zhang 2018; Wang et al. 2020a, b). Considerable research

has focused on the effects of land use changes on ecosystem services and analyzed the effects of different land use patterns and land use intensities on ecosystem services (Fu and Zhang 2014). Generally, the method of ecosystem service value coefficient analysis evaluation based on land use is the most widely used method at present. (Wang et al. 2020a, b).

Mineral resource exploitation affects a large amount of land in China, as 95% of energy, 70% of agricultural production materials, and more than 80% of industrial raw materials are obtained by mining. Most open-air coal mines are located in drought-prone, semi-arid ecologically fragile areas (Lei et al. 2020; Bradshaw et al. 2000). Currently, considerable research is focused on local utilization types of ecosystem services in the context of administrative regions and natural ecosystems (Guan et al. 2021; Peng 2021; Bao et al. 2021; Lin et al. 2021; Guo et al. 2021; Qi et al. 2021). In addition, modeling and other research methods are employed to examine variations in ecosystem services (Ning et al. 2018; Dun et al. 2015; Lu et al. 2015). However, research continues to lag regarding the special land use units of open-air mining areas. Compared with underground coal mining, open-air coal mining is more disruptive of regional land use and landscape patterns as well as biological habitats, which leads to major changes in mining area ecosystem service functions and seriously hinders regional economic and social sustainable development and residents' well-being (Caillault et al. 2013; Sha and Tian 2010; Lu et al. 2015). As such, there is an urgent need for research examining land use and ecosystem service value changes due to open-pit coal mining in ecologically fragile environments.

Due to reform and development efforts, the Inner Mongolia region has made important contributions to energy development and economic development in China. However, Inner Mongolia is an important ecologically sensitive area in the north that should function as an ecological safety barrier, but this function has been adversely affected by mining. This study examined the Shengli coalfield in the eastern Inner Mongolia Highlands, where disturbance of the surface has occurred due to peeling of soil rock formations, coal seam mining, solid backfilling, and surface soil backfilling and reclamation. The present study analyzed the changes in land use and ecosystem service values to reveal the impact of land use evolution for mineral extraction on the value of the ecosystem. The results of this study provide a reference for the rational development and protection of mining regions, which is important for regional economic and social development.

Beginning in 2005, a policy of returning farmland to forest and grassland was instituted, and since then, the amount of cultivated land has decreased. A number of scholars have used a three-level ecological evaluation index system to evaluate the ecological quality of the Shengli coalfield, modeling the effects of factors such

as diversity, representative air pollution concentrations, heavy metal pollution, soil erosion, and groundwater pollution. Their results have shown that the ecological quality of the Shengli coalfield is very high and meets the requirements for sustainable development (Ma and Wang 2006). However, the mining area ecosystem service value has declined year by year, indicating that ecological quality has been compromised in the mining area (Rayburn and Schulte 2009). In 2020, the Inner Mongolia Autonomous Region drafted a policy titled "Opinions on Promoting the High-Quality Development of Coal Industries". This policy enacted strict new coal mine access requirements and demonstrated that the government has taken greater control of the coal industry.

The objectives of the present study were: (1) use GEE (Google Earth Engine) platform to characterize the land use coverage of the region and clarify the structure and changes in land use; (2) evaluate variations in the local service values in the mining area based on land use condition data and the equivalent factor method for assessing regional ecosystem services; (3) exploit the impact of land use changes on the value of ecosystem services

to ensure the sustainable use of local land resources and provide decision support for environmental protection efforts, based on data regarding changes in land use and ecosystem service values.

2 Study area

Shengli coalfield ($43^{\circ} 54' 15''$ – $44^{\circ} 13' 52''$ N, $115^{\circ} 24' 26''$ – $116^{\circ} 26' 30''$ E) is located in the northwest of Xilinhart, Inner Mongolia Autonomous Region, Northwest Susu and Illlamise. The area appears as a northeast to southwest strip on a map, and the towing is 45 km long, the tendency width is 7.6 km, and the coal-containing area is 342 km^2 (Fig. 1). There are two coal segments in the coal mine: the chalk is a coal section in the chalk, and there are seven coal sections. There are seven coal mining groups, with an average depth of 200–500 m, with an average thickness of 8–60 m and 1989 proven reserves of 15.932 billion tons; the reserved reserves comprise 15.931 billion tons. The mining area elevation ranges from 970 to 1212 m, and the terrain follows slow waves of ups and

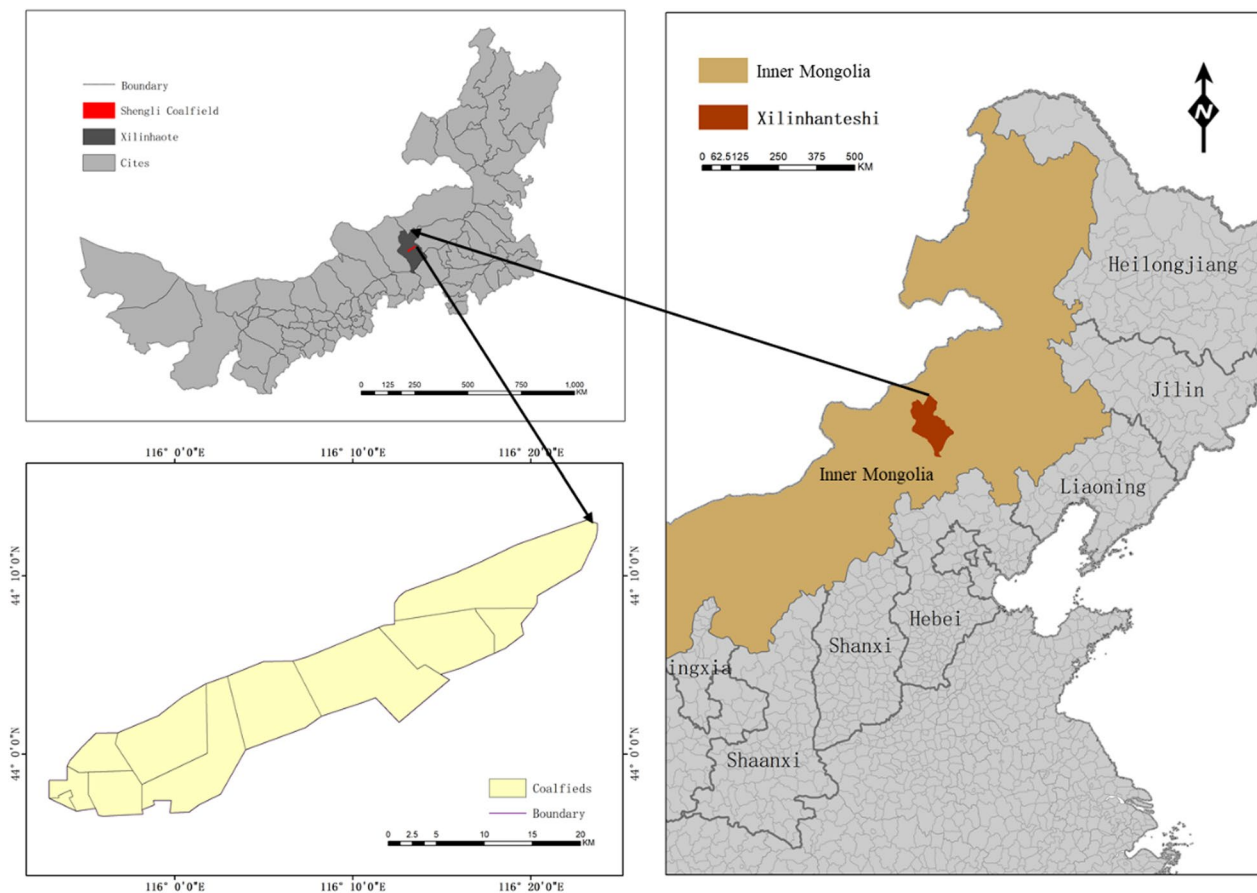


Fig. 1 Location of Shengli coalfield

downs in the piedmont plain. The area has a temperate continental climate and is a typical temperate, semi-humid, half-dry region with an extreme maximum temperature of 38.3 °C and extreme minimum temperature of −42.4 °C. The average temperature is 1.7 °C, the annual maximum precipitation is 481.0 mm, the annual minimum precipitation is 146.7 mm, and the average annual precipitation is 294.74 mm. The annual evaporation is 1794.64 mm, with spring vents; the wind speed ranges from 2.1 to 8.4 m/s, and the soil organic matter content and soil fertility are poor. The area is an important source of China's green livestock products. There is high-quality natural grassland throughout the district, encompassing 13,786 km², and vegetation coverage is approximately 40%. The main land use types near the study area are grassland, mining land, and unused land (Xiao et al. 2020b).

3 Materials and methods

3.1 Data and classification of LUCC

We downloaded Landsat images of the Shengli coalfield research zone for the years 2000, 2005, 2010, 2015, and 2020 via the geospatial data cloud, based on ENVI, using the same time interval and the same time phase remote sensing data in order to reduce errors due to seasonal differences. Based on the pretreatment of the band combination of remote sensing images, geometric correction, projection conversion, image mosaics, and regional crops, the research area was classified according to five types: construction land, vegetation, cultivated land, bare land, and water bodies. The relevant social statistics related to the training area of the Shengli coalfield, the coal mine distribution maps, topographic maps, and statistical year data were reserved for later analysis.

3.2 Random forest algorithm

The random forest method includes two primary processes: training and classification. The steps for generating a Random Forest are as follows: (1) In the training process, K sample subsets are randomly selected from the training samples using a bootstrap self-help sampling method to build K trees. Samples not selected are used as out-of-bag data, for a total of K out-of-bag data. (2) All nodes of each tree have m returned extracted features (M is less than the total number of features in the corresponding sample subset m). By calculating the amount of information contained in each feature, one of the M features with the highest classification capacity is selected to split the nodes. (3) Each tree grows

to its maximum without pruning. (4) A random forest is formed from each tree generated. The random forest is used to classify the data that are not involved in the sampling, and the classification results are generated according to the following formula:

$$H(x) = \operatorname{argmax}_Y \sum_{i=1}^K I(h_i(x) = Y)$$

where, $H(x)$ is the final classification result of RF; $h_i(x)$ is the classification result of a single tree; Y is the output variable; and I is an illustrative function. After classification, the kappa coefficient and overall accuracy of each land class classification are obtained and combined with the verification samples. Multi-scale continuity technology is adopted to ensure the consistency of adjacent land class boundaries, and finally, all land use classification results are presented on one map.

3.3 Land use transfer matrix based on overlay analysis

This study performed statistical analyses of land use type data for Shengli coalfield for the years 2000, 2005, 2010, 2015, and 2020. Using ArcGIS software, attribute queries and statistical analyses of these data were conducted for Shengli coalfield with regard to area, scale, and distribution. Thus, it can be seen that during the study period, the main land use types of Shengli coalfield included construction land, vegetation, cultivated land, bare land, and water bodies. Under the same spatial coordinate system, the spatial attribute data of different geographic characteristics of the same area were superimposed to generate multiple characteristics of the spatial region or establish a spatial correspondence between the geographic objects. Based on these results, the land coverage for different phases in the same area were determined using the land utilization data for different years. A two-dimensional land utilization transfer matrix was then drawn. The land use transfer matrix describes the changes in land types over time and space and plays an important role in studying the driving factors, event backgrounds, and microcharacteristics of land type changes. In this paper, the application of the land transfer matrix can intuitively see the historical events in the mining area.

Using the land utilization transfer matrix, it is possible to reflect the case of mutual conversion between two different land utilization types and describe the structural characteristics of the raised land use and highlight an area during the initial and final classes differently during a change in use while at the same time showing better land use types of the space–time evolution process. Using ArcGIS software, the land utilization component of the land use transfer

Table 1 Remote sensing parameters

No.	Satellite	Time	Scale
1	Landsat 5 TM	Jun 5th 2000	30 m
2	Landsat 5 TM	Jun 7th 2005	30 m
3	Landsat 5 TM	Jun 5th 2010	30 m
4	Landsat 7 TM	Jun 10th 2015	30 m
5	Landsat 8 OLI	Jun 7th 2020	30 m

matrix was obtained for the periods 2000–2005, 2005–2010, 2010–2015, and 2010–2020, and a land utilization map was generated from land utilization transfer matrices to study the land use types of the Shengli coalfield. Thus, the transition between land use types in the Shengli coalfield and the inflow and outflow direction of each land type were analyzed using the following mathematil expression:

$$S_{ij} = \begin{vmatrix} s_{11}s_{12} \cdots s_{1n} \\ s_{21}s_{22} \cdots s_{2n} \\ \dots \dots \dots \\ s_{1n}s_{n2} \cdots s_{nn} \end{vmatrix} \quad (1)$$

where, *S* is the land use area; *ij* is the type of land utilization at the beginning of the study period, and *n* is the number of land uses.

3.4 Calculation of ecosystem service value

Based on the economic value of the unit area ecosystem, the value coefficient multiplies the ecosystem value obtained by the area of the corresponding land use type (Costanza et al. 1997; Kindu et al. 2016). Xie et al. (2001, 2003) developed an equivalent factor method derived from the unit value

method. Assuming that the equivalent of the farmland unit area is 1, the equivalence of other ecosystems can be quantified by comparing their utility with farmland food production (Lin et al. 2018). This method has been widely used in ecosystems service value research. Therefore, this study adopted the 2003 revised ecosystem service value table of Xie et al. (2003) (Table 1), and the construction land equivalent value was 0. According to relevant research, the economic value of the ecological service value equivalents was approximately 1.0 relative to the national average grain market values, which were calculated for 2000, 2005, 2010, 2015, and 2020 ESVs (Ecosystem Service Values).

According to the actual situation in the victory mining area, using the ecosystem service value measurement method of Costanza et al. (1997) and Xie et al. (2003), the following formula was used to calculate the ecosystem service value of various land use types of the victory mine:

$$ESV = \sum(A_i \times VC) \quad (2)$$

where, *ESV* indicates the ecosystem service value (in Yuan); *A* is the area of the land utilization type within the research area (km²); *VC* is the coefficient of ecosystem services (Yuan/km²); and *i* is the type of land use.

4 Results

4.1 Analysis of LUCC in mining areas

4.1.1 Structural changes in LUCC

LUCC plays an important role in monitoring mining processes, and the resulting information is helpful for

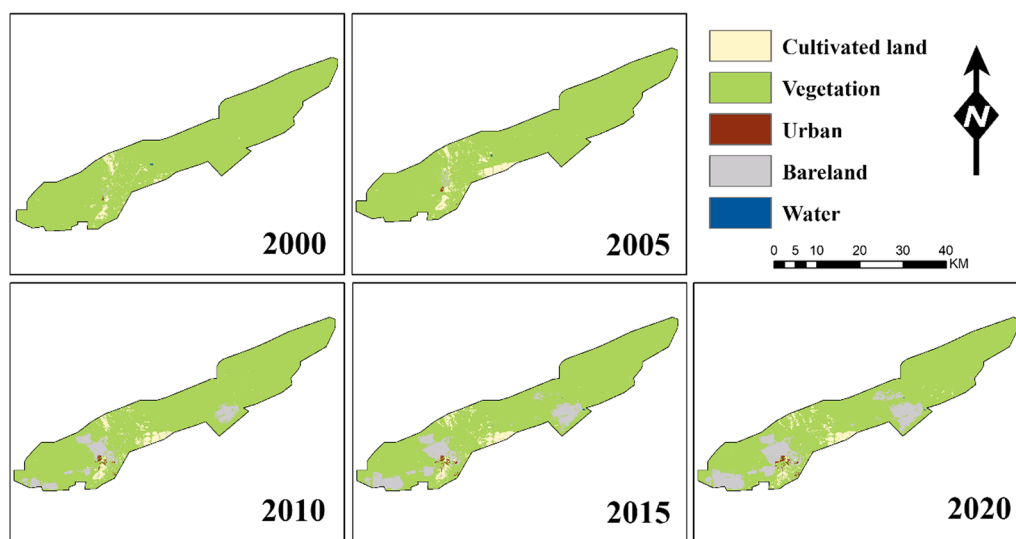


Fig. 2 Mining area distribution of land use in different periods in the Shengli coalfield

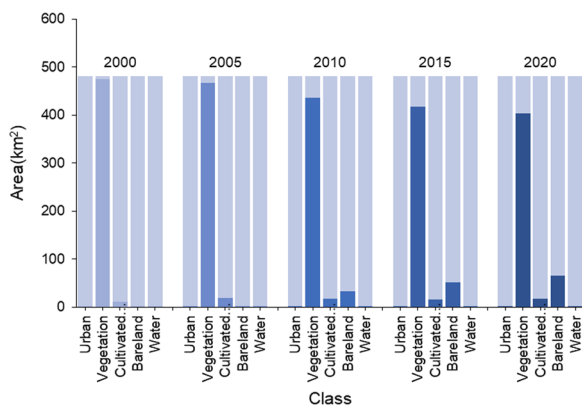


Fig. 3 Statistical data regarding LUCC classifications

reconstructing optimized land use patterns (Cheng et al. 2019). The total classification accuracy of the whole map was 81.73%, with a total kappa coefficient of 0.81. The current land use types in the mining area between 2000 and 2020 are shown in Fig. 2. In 2000, the Shengli mining area was dominated by vegetation overall, but a small amount of cultivated land was distributed in the southwest. From 2000 to 2005, the vegetation coverage in the northeast and southwest was good, and some cultivated land was added in the south-central area. From 2005 to 2010, a portion of the vegetation area in the south-northeast and

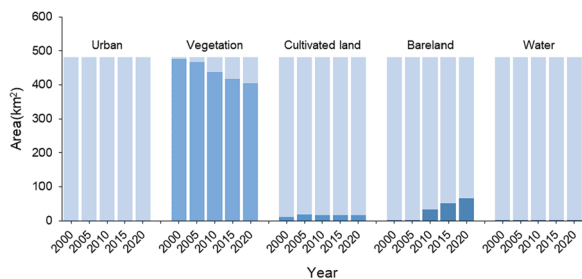


Fig. 4 Area affected by various LUCC changes from 2000 to 2020

Table 2 China terrestrial ecosystem unit area ecological service value equivalents

Indicator	Vegetation	Cultivated land	Water	Bare land
Gas regulation	0.8	0.5	0	0
Climate regulation	0.9	0.89	0.46	0
Water conservation	0.8	0.6	20.38	0.03
Soil formation & protection	1.95	1.46	0.01	0.02
Waste treatment	1.31	1.64	18.18	0.02
Biodiversity protection	1.09	0.71	2.49	0.34
Food production	0.3	1	0.1	0.01
Raw materials	0.05	0.1	0.01	0
Entertainment culture	0.04	0.01	4.34	0.01

Table 3 Changes in land use type in the mining area of Shengli coal-field during different periods (km²)

Period	Urban	Vegetation	Cultivated land	Bare land	Water
2000–2005	0.15	−9.01	7.72	1.19	−0.06
2005–2010	0.88	−29.58	−2.11	30.87	−0.05
2010–2015	0.47	−19.36	−0.25	19.05	0.09
2015–2020	0.25	−13.88	0.21	13.43	−0.01

southwest of the mining area was transformed into bare land or construction land, and the area of cultivated land in the central region was declined. From 2010 to 2015, the area of bare land and construction land continued to increase as that of vegetation land continued to decrease. From 2015 to 2020, the area of bare land and construction land continued to increase. Across the whole study area, the vegetation coverage in the mining area has remained good for many years (Fig. 3). From 2000 to 2020, the vegetation area decreased year by year, the bare land increased year by year, the proportions of construction land and water area were the lowest, and the cultivated land remained basically stable since 2005 (Fig. 4). Vegetation exhibited the largest change in area proportion, whereas water exhibited the smallest (Table 2).

The changes in land use type differed in different periods. With the development of mining in the mining area, construction land and bare land continued to increase, and the large areas of vegetation and cultivated land continued to decrease over the study period. The 2005 to 2010 period exhibited the largest changes in vegetation, construction land, and bare land use types. According to data regarding mineral resources planning for the Inner Mongolia Autonomous Region (2001–2010), by 2005, built mines reached an appropriate scale and reasonable layout through reorganization and transformation, and the mining enterprises in the region achieved large-scale operation and intensive production by 2010. Therefore, 2005 to 2010 exhibited large-scale mining effects. Accordingly, the trends in the

changes of centralized and contiguous land use types were readily determined and revealed the effects on changes in ecosystem service value. Since 2010, with the promulgation of regulations on land reclamation and implementation measures, people have paid increasing attention to environmental protection, and “ecological civilization” has become the theme of the times. In addition, mining area reclamation has received increasing attention, mining has become more scientific and sustainable, mining progress has slowed, and damage to vegetation and cultivated land has declined. With the increase in reclamation activities, the area of cultivated land began to exhibit an increasing trend from 2015 to 2020.

4.1.2 Spatial pattern change in LUCC

Using the ArcGIS 9.2 superposition analysis function, the land utilization transfer matrix was analyzed with regard to land use data for the Shengli coalfield for 2000–2020 (Table 3). There was almost no change in the construction land of the mining area, and vegetation was mainly

transformed into bare land or cultivated land, with transformation areas of 63.66 and 12.36 km², respectively. Cultivated land was mainly transformed into bare land or vegetation, with transformation areas of 0.86 and 5.37 km², respectively. Bare land was mainly transformed into vegetation, with a transformation area of 0.02 km². Water bodies were mainly transformed into vegetation, with a transformation area of 0.06 km² (Fig. 5, Table 4).

4.2 Analysis of changes in ecosystem service values in the Shengli coalfield

Based on the new 2003 China Land Ecosystem Service Value equivalent Table of Unit Area by Xie et al (2003), according to the correction coefficient, one unit ecosystem service value of the Shengli coalfield was calculated at approximately 310 Yuan. We also calculated the value coefficients of ecological system types corresponding to the type of land use. The highest value coefficient was for water areas, which have high ecological value and function in term of water conservation and waste treatment. Vegetation

Table 4 Land use transfer matrix (2000–2020) (km²)

LUCC	2000					
	Urban	Vegetation	Cultivated land	Bare land	Water	SUM
2020						
Urban	0.19	1.55	0.20	0.00	0.00	1.93
Vegetation	0.00	397.99	5.73	0.02	0.06	403.80
Cultivated land	0.00	12.36	4.67	0.00	0.00	17.03
Bare land	0.00	63.66	0.86	0.62	0.05	65.19
Water	0.00	0.09	0.00	0.00	0.00	0.09
SUM	0.19	475.64	11.45	0.64	0.11	488.04

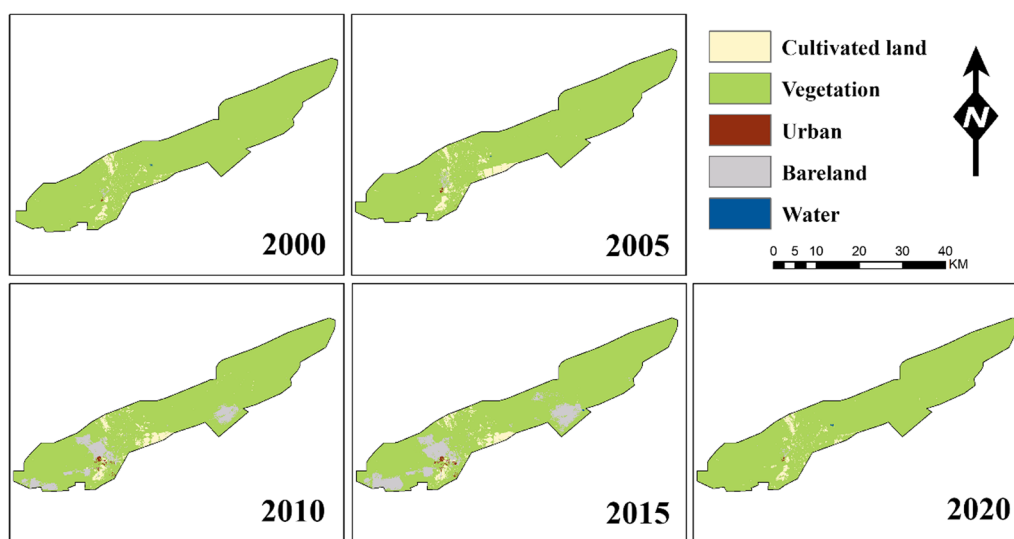


Fig. 5 Maps showing changes in LUCC from 2000 to 2020

Table 5 Ecosystem types and LUCC value coefficients in the Shengli coalfield (Yuan/ha)

Indicator	Vegetation	Cultivated land	Water	Bare land	Constructed land
Gas regulation	248.0	155.0	0.0	0.0	0.0
Climate regulation	279.0	275.9	142.6	0.0	0.0
Water conservation	248.0	186.0	6317.8	9.3	0.0
Soil formation & protection	604.5	452.6	3.1	6.2	0.0
Waste treatment	406.1	508.4	5635.8	6.2	0.0
Biodiversity protection	337.9	220.1	771.9	105.4	0.0
Food production	93.0	310.0	31.0	3.1	0.0
Raw material	15.5	31.0	3.1	0.0	0.0
Entertainment culture	12.4	3.1	1345.4	3.1	0.0
Total	2244.4	2142.1	14,250.7	133.3	0.0

Table 6 Ecosystem service values in the Shengli coalfield from 2000–2020 (billion Yuan)

Year	Index	Urban	Vegetation	Cultivated land	Bare land	Water	SUM
2000	Value (billion Yuan)	0.00	10.675	0.245	0.001	0.018	10.939
	Percentage (%)	0	97.59%	2.24%	0.01%	0.16%	100.00%
2005	Value (billion Yuan)	0.00	10.473	0.411	0.002	0.009	10.895
	Percentage (%)	0	96.13%	3.77%	0.02%	0.08%	100.00%
2010	Value (billion Yuan)	0.00	9.809	0.366	0.044	0.002	10.22
	Percentage (%)	0	95.98%	3.58%	0.43%	0.02%	100.00%
2015	Value (billion Yuan)	0.00	9.374	0.360	0.069	0.014	9.818
	Percentage (%)	0	95.48%	3.67%	0.70%	0.14%	100.00%
2020	Value (billion Yuan)	0.00	9.063	0.365	0.087	0.012	9.527
	Percentage (%)	0	95.13%	3.83%	0.91%	0.13%	100.00%

and cultivated land exhibited similar ecological value coefficients, and both have high ecological values and functions in terms of soil formation and protection as well as waste treatment. The difference between vegetation and cultivated land is that the ecological value coefficient of biodiversity protection of vegetation is higher, and the ecological value coefficient of food production of cultivated land is higher. The ecological value coefficient of bare land was the lowest, which is primarily reflected in biodiversity protection. Generally speaking, the ecological value coefficient corresponding to each land use type in the mining area corresponded to its ecological value function (Table 5).

According to the ecological value coefficients and land utilization areas, the ecosystem service values (Table 6) were calculated for 2000, 2005, 2010, 2015, and 2020. Between 2000 and 2020, the total ecosystem service value of the Shengli coalfield exhibited a significant downward trend, declining from 10.939 billion Yuan to 9.527 billion Yuan. According to the rates of change in ecosystem service values of the Shengli coalfield (Tables 6, 7), the value of vegetation ecosystem services was the highest in 2000.

Beginning in 2000, the ecosystem service value of vegetation decreased year by year, with the highest change of

Table 7 Changes in ESV in the Shengli coalfield over 5-year intervals (billion Yuan)

Period	Urban	Vegetation	Cultivated land	Bare land	Water
2000–2005	0.00	−2.02	1.65	0.02	−0.09
2005–2010	0.00	−6.64	−0.45	0.41	−0.07
2010–2015	0.00	−4.34	−0.05	0.25	0.12
2015–2020	0.00	−3.12	0.05	0.18	−0.02

6.64 billion Yuan occurring between 2005 and 2010. The service value of bare land ecosystems increased year by year, with the highest increase of 410 million Yuan occurring between 2005 and 2010. The ecosystem service value of cultivated land increased by 165 million Yuan between 2000 and 2005. The ecosystem service value of water areas decreased year by year except for the period 2010 to 2015, during which it increased before decreasing slightly from 2015 to 2020. In general, the total ecosystem service value decreased year by year from 2000 to 2020. The ecosystem service value of vegetation in the mining area was the highest, followed by cultivated land, and the ecosystem service value of bare land was the lowest (Fig. 6).

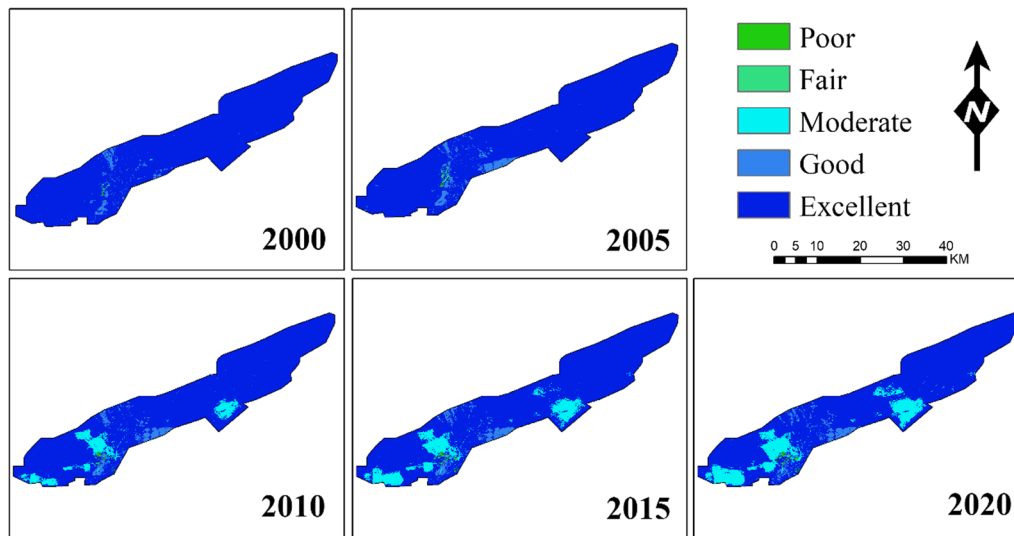


Fig. 6 Maps of ESV Classification from 2000 to 2020 Using the Natural Segment Method

4.3 Influence of LUCC on ecosystem service values in the coalfield

By analyzing the relationship between land use changes and ecosystem service value changes, we can more intuitively clarify the impact of land use on ecosystem service values. Changes in the areas of different land use types can cause large or small changes in the value of ecosystem services. In terms of change rate, the change rate of land use area of vegetation, cultivated land, and water bodies was positively correlated with the rate of change in ecosystem service value, whereas the rate of change for bare land and construction land was not particularly significantly correlated with the rates of change in ecosystem service values. Overall, the ecosystem rate of change was clear compared with the corresponding changes in the range of land area. It can be seen that land use changes have a significant impact on changes in ecosystem service values.

The inflection point of cultivated land change occurred around 2005. Before 2005, the service value of cultivated land ecosystems increased gradually, and vegetation decreased gradually over the same period. Since the implementation of the policy of returning farmland to forest and grassland in Inner Mongolia around 2005, the area of cultivated land has slowly decreased. Mining has changed the surface vegetation coverage, which declined year by year, and the water area also decreased, with a corresponding decrease in the service value of local ecosystems. On the whole, the change range of vegetation was significantly smaller than that of cultivated land. The reason for this difference is that in calculating the ecological service value coefficient, the food production value coefficient of cultivated land is much larger than that of vegetation, whereas

the ecological benefit value component of the value coefficient composition of vegetation is higher, which is not obvious over a short time period. The ecosystem service value coefficient of water areas was the highest. Therefore, taking 2010 as the turning point, the area of land use decreased sharply, increased significantly, and then declined again. Accordingly, the value of ecosystem services also changed, and the change range was much greater than that of land use. These data also provide an important reference for future preparation of land and space ecological protection and restoration planning programs, long-term follow-up monitoring, and evaluations of effectiveness.

On the whole, the ecosystem service value of the Shengli mining area has decreased year by year over the past 20 years as the area of vegetation and water bodies with high ecosystem service value coefficients decreased. The area of bare land with a low ecosystem service value coefficient increased significantly. Although cultivated land increased slightly, it failed to make up for the increase in area of bare land with a low service value coefficient (Figs. 7, 8).

5 Discussion

The impact of coal mining on the ecosystem has the characteristics of a long cycle, wide range, and deep degree. The cumulative negative ecological effect has intensified the ecological vulnerability in eastern Inner Mongolia and has become one of the key factors in reducing the value of ecosystem services (Wu 2020). In addressing the scientific problem of "temporal and spatial variation law and correlation of land use and ecosystem service value in mining area", taking the Shengli mining area, a typical arid and semi-arid

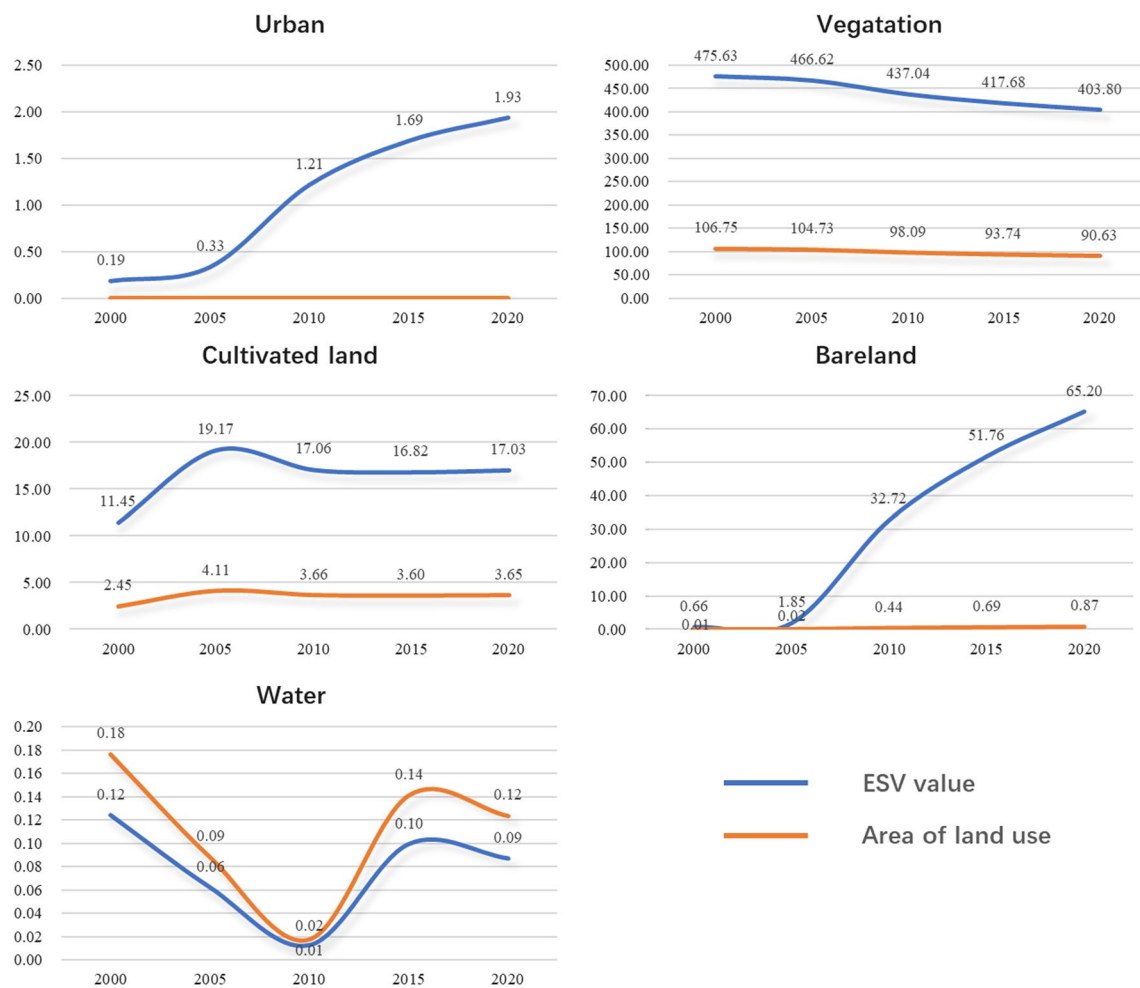


Fig. 7 Variations in land use area and ecosystem service value in 2000–2020 (The X-axes indicate year, and the Y-axes indicate variation in land use area. Blue lines indicate the ESV of the type of LUCC, and orange lines indicate the area of land use type)

vulnerable area in Inner Mongolia, as an example, this study quantitatively evaluated the interaction between land use changes and key ecosystem services based on the calculation and analysis of land use types and changes in land use area. The correlation between land use changes and temporal and spatial evolution of ecosystem services was revealed. Relevant published research has strongly demonstrated the negative impact of open-pit mining on ecosystem services and suggested that mining area ecosystem management should make management decisions from the perspective of the whole ecosystem in order to truly realize coordination between resource development and environmental protection efforts. In the future government management decision-making, this method would enable continuous tracking of the evolution of land use patterns and the changes in ecosystem services in this area, enabling the establishment of a tracking and monitoring system and early warning mechanism to appropriately slow the cumulative negative ecological effects in mining areas.

5.1 Utility of the method

This study preliminarily analyzed the impact of open-pit mining on ecosystem services and intuitively analyzed the land use changes in the Shengli mining area over the past 20 years using land use matrix analysis and mapping methods that conform to the characteristics and regularities of impacts in the mining area. Using the equivalent method based on the local coefficient correction in Inner Mongolia, the changes in ecosystem services were calculated, and these changes were correlated to a degree with the law of land use changes. However, research into the mechanism underlying these impacts is lacking. In addition, this study comprehensively considered the specific situation of the research frontier and the research area, selecting nine types of ecosystem services as the research objects, but we did not calculate all ecosystem services in detail. Calculations of ESV revealed that the total ESV of areas decreased year by year. The rules of ESV change for different land types differ.

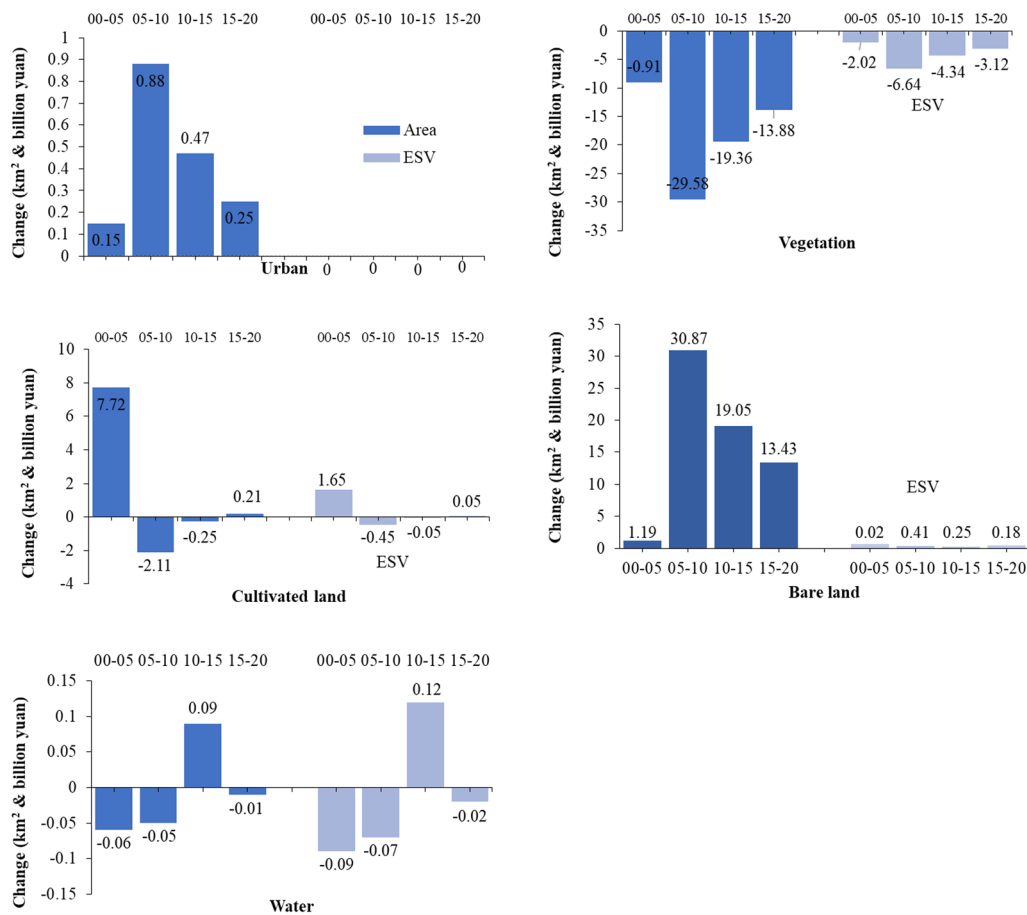


Fig. 8 Variations in land use area and ecosystem service value per change period

The relevant conclusions of the present research provide support for the optimal regulation of mining and reclamation projects based on ecosystem services in the Shengli mining area and address the main contradiction between mining and reclamation and ecological environment protection efforts. Our results clarified this issue. However, additional research is needed regarding the mechanism underlying the effects of open-pit mining area on a wider variety of ecosystem services. In the future, we will examine the mechanism through which ESV is related to mining in greater detail.

5.2 Implications for variations in the value of ecological services

Since 2000, increasing research has focused on ecosystem service values, but most of the research has been carried out on the watershed, regional, or macro scales, and the research objects have mostly been natural ecosystems. Little research has examined special natural artificial ecosystems such as open-pit mining areas. Due to intense disturbances associated with human activities, the land use structures and ecosystem service values of open-pit mining areas are expected

to change greatly. Examination of the regularity of land use changes between 2000 and 2020 revealed that the areas of vegetation, cultivated land, and water bodies in the Shengli mining area of Inner Mongolia exhibited a decreasing trend, whereas the areas of bare land and construction land showed an increasing trend. The largest change in the area proportion was that of bare land, and the smallest change was that of water bodies. With regard to changes in ecosystem service value, the total ecosystem service value of the Shengli mining area decreased from 10.939 billion to 9.527 billion Yuan. However, studies by Wang Ning (2020) and others showed that although the total value of ecosystem services in the Inner Mongolia Autonomous Region changed little from 1990 to 2018, it did increase. In contrast, it can also be seen that mining activities have a great impact on ecosystem service values. Calculation of ESVs revealed that the total ESV by area decreased year by year. The ESV change rules for different land types differ. The ESV of bare land increased, whereas the ESV of vegetation decreased year by year, and the inter-annual change in the ESV of cultivated land and water areas was irregular. Mining is an important factor affecting the change in ecosystem services.

From construction to restoration, a mining operation can be divided into many complex stages, such as mine ground preparation, ore body drainage, mine capital construction, normal production of the mine, and surface recovery and utilization. Therefore, during mineral exploitation projects, the land use mode will change many times, resulting in drastic changes in the ecological landscape pattern. The significant vegetation damage caused by mining caused the ESV of vegetation to decrease year by year, whereas the inter-annual variation in the ESVs of cultivated land and water areas was irregular. Land use has an impact on ecosystem service values, but the degree of the impact remains uncertain. Therefore, greater effort should focus on reducing mining activities in the region. Our research suggests that reducing mining activities would be useful in managing the environment and making sure ESVs do not decrease.

5.3 Consideration of the cultural functions of construction land and research accuracy

Based on the evolution of land use patterns in the Shengli mining area over the past 20 years, this study analyzed the impact of mining on the changes in ecosystem service values, summarizing the results from the perspective of time and space. However, many problems remain to be solved, which will require in-depth consideration. First, the cultural function of construction land must be considered. The current method of calculating ecosystem service functions based on changes in land use type is relatively common, but the value equivalent of construction land is often set to 0 in the calculation. In the next step, the equivalent value can be further optimized to be more comprehensive and objective in the calculation of ecosystem service values. Second, due to the availability of remote sensing images, the spatial resolution of the land use classification data of the Inner Mongolia open-pit mining area obtained in this study was not sufficient to identify and support a more detailed land use and ecological effect assessment of the mining area.

5.4 Further promotion of multi-scale research

It is necessary to expand the space–time scale of research and carry out multi-scale analyses of changes in ecosystem services caused by open-pit mining and reclamation efforts. Limited by the available data, the period of this study was 2000–2020, and only one spatial scale of the Shengli mining area was considered. In terms of time scale, it was not refined from the stages of basic construction, mining practices, reclamation and management, and protection, according to the implementation characteristics of the project in the Shengli mining area. Other problems included no reclamation after mining or no timely recovery of disturbances in the initial stage of reclamation within the research period. The

time scale can also be extended for future research to more comprehensively, systematically, and objectively evaluate changes in ecosystem service values and conduct simulation evaluations based on the measures taken.

In terms of spatial scale, the project area scale can be varied in future research to more deeply explore the mechanisms by which mining and reclamation impact ecosystem services and expand the research to cover the Xilin Gol League of Inner Mongolia provincial scale to elucidate the impact of open-pit mining and reclamation activities on ecosystem services. Based on the characteristics and relationship between the impact of open-pit mining and reclamation on ecosystem services at different scales, future research could focus on the development of a multi-scale coupling model.

5.5 Construction of a multi-scale ecological monitoring system in the mining area

Ecological monitoring, including the monitoring of existing ecological problems and ecological restoration effects, is a very important basic work. Worldwide, mining activities have impacted ecological health to varying degrees. If the variety of possible impacts can be predicted in advance at minimal expense and response plans can be formulated in advance, the negative impacts of coal mining on the environment could be greatly reduced. With recent advances in 3S technology, it is now possible to construct a multi-scale mining area ecological monitoring system to control environmental damage caused by coal mining and occasional natural disasters (Wu 2020). Future coal mining projects could implement a mining area ecological monitoring system with varying precision and multi-dimensional scales based on adherence to the concepts of sustainable development and the principles of mining during reclamation. Monitoring would enable the discovery of violations of mining laws and warn of associated risks. Combining hyperspectral data, UAV (unmanned aerial vehicle) photogrammetry, portable ground object spectrometry, and other means of simultaneous monitoring would enable comparisons of historical data regarding mining and reclamation and permit in-depth studies of the impact of open-pit mining in the Shengli mining area. This would also facilitate large-scale studies of arid and semi-arid areas in terms of ecosystem services and encourage local governments to propose feasible ecological protection and restoration measures.

5.6 Establishment of a long-term mechanism for realizing the value of ecological products

Mining areas are usually in fragile ecological environments. Protecting, maintaining, and improving the stability of the ecosystem service function and value of mining areas are

important for enhancing the well-being of nearby residents and maintaining the environment of the mining area. With the publishing of the guidance document regarding the mechanism of realization of the value of ecological products and the establishment and improvement of relevant mechanisms, public demand for a better ecological environment is continually increasing. In recent years, natural resource and ecological environment departments have issued proposals advocating for ecological restoration, system governance, and comprehensive development to increase the supply capacity of ecological products in areas damaged by mining activities. This could also increase value promotion and value spillover of ecological products after ecological restoration by combining these efforts with land spatial layout, land use adjustments, and industrial policies. To establish a long-term mechanism for realizing the value of ecological products in mining areas with fragile ecological backgrounds, the environment of mining areas must be protected through unified planning and design efforts covering the entire mining cycle. This should also include "integrated planning, integrated implementation, and integrated effects" of mineral resource mining, ecological protection and restoration, industrial development, and improvement in order to realize the value of ecological products.

6 Conclusions

By analyzing the relationship between land use changes and ecosystem service values, we can clarify the impact of various land uses on ecosystem service values.

- (1) Vegetation is the primary land use type in the Shengli mining area, followed by bare land and cultivated land. From 2000 to 2020, the extent of construction land in the mining area changed very little. Vegetation and water bodies showed a decreasing trend, whereas bare land and cultivated land showed an increasing trend. The largest change in area proportion was in bare land, and the smallest was in water bodies.
- (2) Vegetation was transformed primarily into bare land and cultivated land, with transformation areas of 63.66 and 12.36 km², respectively. Cultivated land was transformed primarily into bare land and vegetation, with transformation areas of 0.86 and 5.73 km², respectively. Bare land was transformed primarily into vegetation, with a transformation area of 0.02 km². Water bodies were transformed primarily into vegetation, with a transformation area of 0.06 km².
- (3) The total ecosystem service value of the mining area decreased from 10.939 billion Yuan to 9.527 billion Yuan over the study period. The vegetation ecosystem service value was the highest, followed by cultivated
- (4) On a spatial scale, the total ecosystem service value of the Shengli mining area decreased year by year, whereas the bare land ecosystem service value increased year by year, the vegetation ecosystem service value decreased, and the inter-annual change in cultivated land and water ecosystem service values varied.

Authors' contributions LZ: Writing original draft & data processing, reviewing, and editing. XZ: Reviewing, editing & corresponding. YZ: Reviewing. JZ: Reviewing. JG: Data processing & typesetting. ZZ: Checking and proofreading. YC: Checking and proofreading. XYS: Checking and proofreading. LY: Checking and proofreading. LW: Checking and proofreading. YQ: Checking and proofreading.

Declarations

Competing interests The authors declare that they have no competing interests.

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