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RESEARCH

Division of carbon sink functional areas and path to carbon neutrality in coal mines

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Abstract

Remote sensing image data of typical mining areas in the Loess Plateau from 1986 to 2018 were used to analyze the evolution of land use, explore the division of carbon sink functional areas, and propose carbon neutrality paths to provide a reference for the coal industry carbon peak, carbon-neutral action plan. Results show that (1) land use has changed significantly in the Pingshuo mining area over the past 30 years. Damaged land in industrial, opencast, stripping, and dumping areas comprises 4482.5 ha of cultivated land, 1648.13 ha of grassland, and 963.49 ha of forestland. (2) The carbon sink functional areas of the Pingshuo mining land is divided into invariant, enhancement, low carbon optimization, and carbon emission control areas. The proportion of carbon sinks in the invariant area is decreasing, whereas the proportion in enhancement, low carbon optimization, and carbon emission control areas is gradually increasing. (3) The carbon neutrality of the mining area must be reduced from the entire process of *stripping–mining–transport–disposal–reclamation*, and carbon emissions and carbon sink accounting must start from the life cycle of coal resources. Therefore, carbon neutrality in mining areas must follow the 5R principles of *reduction, reuse, recycling, redevelopment*, and *restoration*, and attention must be paid to the potential of carbon sinks in ecological protection and restoration projects in the future.

Keywords Land use · Pingshuo mining area · Carbon neutrality · Functional area · Carbon sink

1 Introduction

Climate change is a major global challenge facing mankind that has attracted worldwide attention (Mallapaty 2020). Faced with the ever-changing climate situation, the Paris Agreement clearly states that the world must do its utmost to control global warming within 1.5 °C and achieve net-zero emissions of greenhouse gases, also known as carbon neutrality, in the second half of the 21st century (Kriegler et al. 2018; Van Vuuren et al. 2018). Carbon neutrality has become a global consensus and is the mainstream direction of future development (Gupta and Garg 2020). By the end of 2020, more than 100 countries around the world have made carbon neutrality commitments and formulated action plans (Capros et al. 2019). For example, the European Commission proposed the European Green Agreement, which formulated a roadmap for the EU to achieve carbon neutrality by 2050; France formulated a circular economy law to provide support for environmental-related fields; Germany announced a fiscal plan to reduce the carbon footprint; and Finland banned coal power generation (Capros et al. 2019; Lund 2017; Salvia et al. 2021).

China has become the world's second-largest economy, and the problems of environmental damage, inefficient use of resources, and extensive land use caused by economic development have become increasingly prominent (Mei et al. 2020). In December 2020, China announced that it expects to achieve carbon peaks by 2030 and carbon neutrality by 2060 (Mallapaty 2020). Coal resources are the basic and main energy source in China, and to achieve the goal of carbon neutrality China must start with the coal industry and realize a low-carbon and green coal industry chain from production to processing, to utilization (Guo et al.

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2018; Wang et al. 2021; Xu et al. 2016). Coal consumption contributed 72% of China's carbon emissions and 19% of global emissions (Wang and Li 2016). According to the BP Statistical Review of World Energy 2020, China's total CO_2 emissions were 9.826 billion tons in 2019, and coal was the main source. In 2019, China's coal output was 3.75 billion tons, and the coal consumption was 3.97 billion tons, which makes it a large producer and consumer of coal resources in the world (Guo et al. 2018). The mining areas are special and complex geographic areas (Zhang et al. 2015), and long-term large-scale mining has changed the landscape structure, reduced its ecological function, destroyed land resources, and caused numerous serious ecological problems (Hendrychova and Kabrna 2016; Xu et al. 2021).

Arable land, forestland, and grassland are the main sources of carbon sinks (Zhou et al. 2020), and the carbon storage function of the ecosystem is closely related to land use types (Xu et al. 2016). Ecological restoration projects can transform land use types and convert damaged land into forest, arable, and grassland, significantly affecting carbon balance and carbon storage (Boisvenue et al. 2012; Cui et al. 2019). To improve ecosystem services, the Chinese government has initiated a series of ecological restoration projects (Ouyang et al. 2016), which have contributed to the mitigation of carbon dioxide emissions to a large extent (Kong et al. 2020). In the past 10–15 years, the provincial forest area has increased by 0.04–0.44 million hectares per year (Wang et al. 2020). Studies on the carbon storage function of the watershed ecosystem in the ecological restoration project found that carbon storage changed significantly after the project was implemented (Zhou et al. 2020). The regional low-carbon development strategy is formulated according to the division of carbon sink functional areas, which can be divided into the carbon emission control area, carbon emission total control area, carbon sink area, carbon budget balance area, and low carbon optimization area (Zhao et al. 2014). To achieve the goal of carbon neutrality, China must start using zero-emission energy to generate electricity, use clean energy, and strengthen the research and development of carbon capturing and carbon storage technologies (Mallapaty 2020).

The development of China's mineral resources mainly includes underground and open-pit mining. Compared with underground coal mines, open-pit coal mines have a greater

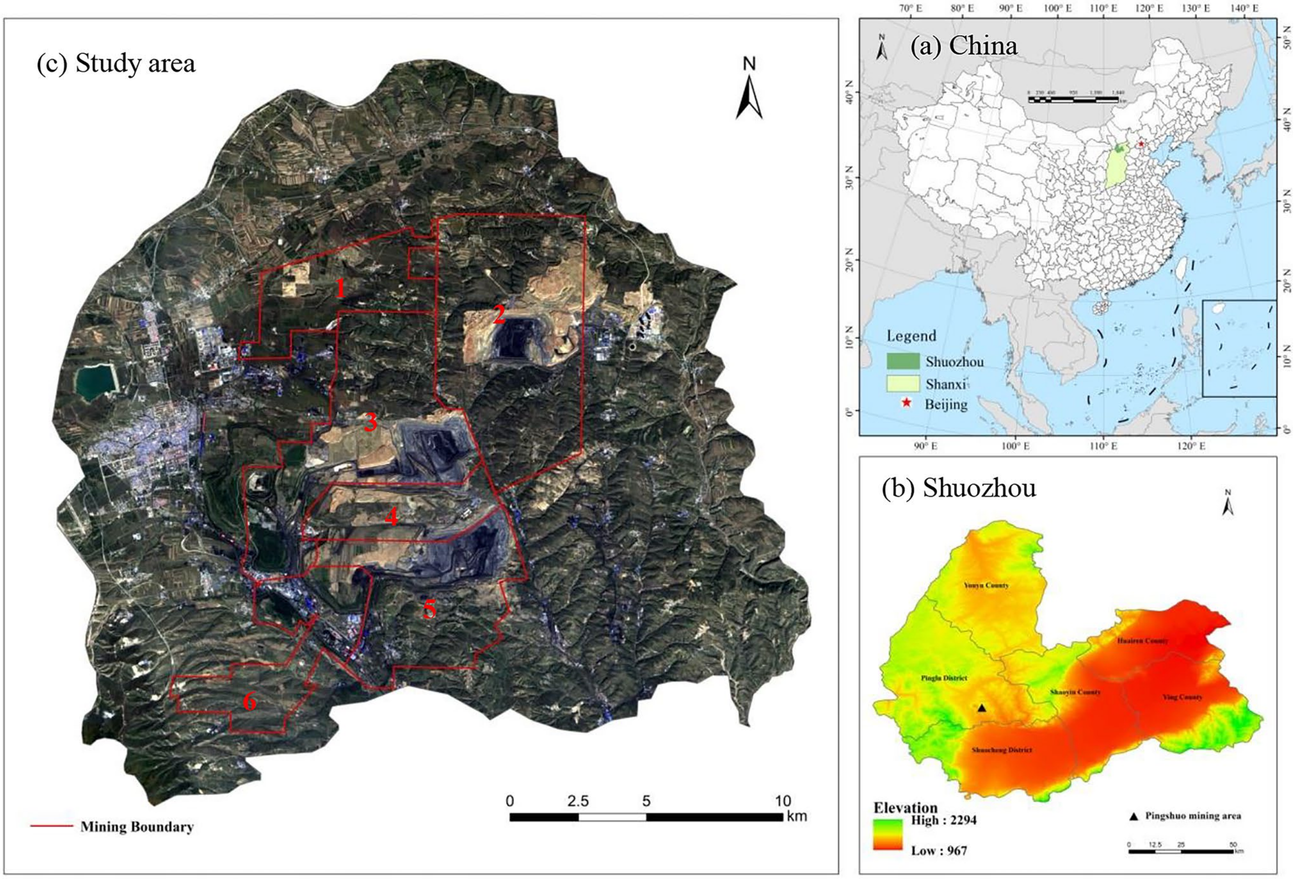

Fig. 1 Study area. Notes: 1 is Antaibao underground mining, 2 is Donglutian open-pit coal mine, 3 is Antaibao open-pit coal mine, 4 is Anjialing underground mining, 5 is Anjialing open-pit coal mine, 6 is Anjialing underground mining

scale and degree of damage to land (Wang et al. 2018). In China, open-pit coal mining directly destroys 0.24 ha of land per 10,000 tons (Gao et al. 2021). Open-pit mining activities require eliminating all surface vegetation, modifying the original landform and landscapes, and destroying soil structures and hydrological regimes (Ahirwal and Maiti 2016; Kumar et al. 2015), resulting in the reduction or even loss of the carbon storage capacity of the soil and vegetation in the mining area. Pingshuo is one of the largest opencast coalmines in China, with a history of more than 30 years since the mine was built in 1985. Past research focused on the physical and chemical properties of reclaimed soil in mining areas (Guan et al. 2021; Zhang et al. 2015), vegetation restoration (Yuan et al. 2018; Zhao et al. 2017), land use changes (Zhang et al. 2020; Zhou et al. 2017), and land expropriation compensation (Cao et al. 2018). However, relevant research on carbon emissions and sinks in large-scale opencast coalmine areas is currently insufficient, especially considering carbon peak and carbon neutrality.

In this study, taking a typical mining area in the Loess Plateau as an example, we use ArcGIS 10.2 and ENVI 4.8 to preprocess and manually interpret remote sensing images to obtain land use data and transfer matrix of the Pingshuo mining area from 1986 to 2018. Based on the "carbon sink–carbon source" perspective, the carbon sinks functional area of the Pingshuo mining area is divided into the carbon sink invariant area, carbon sink enhancement area, low carbon optimization area, and carbon emission control area. The spatial distribution and evolution process of carbon sink functional areas for the past 32 years are analyzed, and the carbon neutrality path of the mining area is elaborated on. The study provides an important reference for the formulation of carbon peak and carbon neutrality action plans in the coal sector.

2 Materials and methods

2.1 Study area

The Pingshuo mining area is located in Shuozhou City, Shanxi Province, China. It is located in the ecologically fragile area of the Loess Plateau, which is one of the largest and most modernized open-pit coal mining areas in China, including three open-pit coalmines and three underground mines (Fig. 1). This area spans 380 km^2 and is rich in coal resources, with a proven geological reserve of 12.75 billion tons (Yang et al. 2021). The Pingshuo mining area has a temperate semi-arid continental monsoon climate, with cool summers and cold winters. The annual rainfall distribution in this area is uneven, the intensity of heavy rain is high, the average annual rainfall is 428.2 mm, and the soil erosion is severe. A large area of extremely degraded damaged land has been produced due to the impact of mining activities. The Pingshuo mining area adheres to the "mining and reclamation" process; the soil microbes, biodiversity, and regional carbon sink capacity of the land ecosystem after reclamation are significantly better than in the original landform (Feng et al. 2019).

2.2 Land use conversion matrix

The land use conversion matrix reflects the dynamics of the mutual transformation of various land use types in the study area in different periods (Lu et al. 2020). This not only includes the land use type area data at a specific time point in the static time, but also includes abundant information about the conversion of the area of each land use type at the beginning and the end of the period (Pontius et al. 2004). The specific calculation formulae are as follows:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} \cdots S_{1n} \\ S_{21} & S_{22} \cdots S_{2n} \\ \vdots & \vdots \quad\ \vdots \\ S_{n1} & S_{n2} \cdots S_{nn} \end{bmatrix}$$

where, S represents land area; n represents the number of land use types; i, j ($i, j = 1, 2, \ldots, n$) are the land use types before and after the land use conversion.

2.3 Carbon function areas

Land use types around mining areas have undergone drastic changes due to mining activities. According to previous research (Zhou et al. 2020), and the actual situation of the Pingshuo mining area in Shanxi Province, the "carbon source–carbon sink" area is divided into four types: the carbon sink invariant, carbon sink enhancement, low carbon optimization, and carbon emission control area (Table 1). Cultivated land, forestland, and grassland are the main sources of carbon sinks, while carbon sink invariant areas mainly refer to land that has not changed during mining activities and urban expansion. Land reclamation projects in mining areas promptly repair damaged land, while the carbon sink function enhancement areas mainly refer to the conversion of damaged land into cultivated land, forestland, and grassland. The mining process consumes a large amount of fossil energy to produce carbon emissions. It also includes carbon emissions from methane escape, explosive use, electricity use, and spontaneous combustion. Carbon emission control areas mainly refer to the mining operation areas of stripping land, industrial land, open pit, and dump, and are the main sources of carbon emissions in mining areas.

2.4 Data source and processing

In this study, remote sensing images from 1986, 2000, 2009, and 2018 were used as data sources. ENVI software and ArcGIS software were used to preprocess the images, supervise the classification, and manual visual interpretation of the four phases of remote sensing images in the mining area, and to obtain land use data for the Pingshuo mining area. The classification results meet the accuracy requirements of above 85%, and the Kappa coefficients are all greater than 0.75. Combined with the actual situation of the Pingshuo mining area, the land use types of the mining area were divided into the following 11 types: arable land, forestland, grassland, urban land, rural land, transportation land, open pit, stripping land, dump, industrial land and water (Table 2).

3 Results

3.1 Land use change

The Pingshuo mining area has undergone significant changes in land use types since the establishment of the mine in 1985. The land is dominated by arable land, forestland, and grassland. The industrial land, stripping land, open pits, and dumping in mining areas have been increasing (Fig. 2), with the arable land area decreasing from 32,119.86 ha in 1986 to 24,191.34 ha in 2018, mainly due to the expansion of construction land and mining activities. From 1986 to 2009, the forestland area was reduced from 8426.73 to 7372.44 ha. With the implementation of the ecological restoration of the mining area and the “Grain for Green” project in the Loess Plateau, the forestland area had reached 9300 ha by 2018, accounting for 18%. The grassland area is decreasing, from 10,655.54 ha in 1986 to 8793.36 ha in 2018, and the fragile ecology and severe soil erosion in the Loess Plateau brought about changes in the farmers’ production patterns.

The area of damaged land has increased rapidly (Fig. 3), and by 2018, stripping land, industrial land, and dump and open pit areas of the Pingshuo mining area were 1109.25, 2243.29, 2856.33, and 914.7 ha, respectively, accounting for 2.14%, 4.34%, 5.52%, and 1.77% of the land area. With the expansion of mining and the production of Dong-Loutian opencast coalmine, after 2009 the area of industrial land increased significantly, from 0.78% to 2000 to 4.34% by 2018. The Pingshuo mining area adheres to the integrated operation process of stripping–mining–transportation–dumping–reclamation, and adopts the ecological restoration mode of mining during reclamation. The depth of the open pit is 100 m, and the topsoil must be stored separately after being stripped, such that it can be used for subsequent land reclamation.

Table 1 Ecosystem carbon sink function areas in Pingshuo mining area

Carbon function areas	Conversion of land use types	Features
Carbon sink invariant area	Arable land - Arable land; Forestland - Forestland; Grassland - Grassland	The carbon sink in the regional ecosystem remains stable.
Carbon sink enhancement area	Open pit - Arable land; Open pit - Forestland; Open pit - Grassland; Dump - Arable land; Dump - Forestland; Dump - Grassland; Stripping land - Arable land; Stripping land - Forestland; Stripping land - Grassland; Industrial land - Arable land; Industrial land - Forestland; Industrial land - Grassland; Arable land - Forestland; Grassland - Forestland	The carbon sink efficiency of regional ecosystem has been significantly improved.
Low carbon optimization area	Arable land - Urban land; Arable land - Rural land; Arable land - Transportation land; Arable land -Water; Grassland - Arable land; Grassland - Urban land; Grassland - Rural land; Grassland - Transportation land; Grassland - Water; Forestland - Urban land; Forestland - Rural land; Forestland - Transportation land; Forestland - Water	The carbon sink level is not high, and the carbon emission pressure is also low.
Carbon emission control area	Arable land - Open pit; Arable land - Dump; Arable land - Stripping land; Arable land - Industrial land; Forestland - Open pit; Forestland - Dump; Forestland - Stripping land; Forestland - Industrial land; Grassland - Open pit; Grassland - Dump; Grassland - Stripping land; Grassland - Industrial land	The main carbon source in the region, it is necessary to take measures to control carbon emissions.

3.2 Land use types conversion

Mining activities occupy a large number of cultivated land, forestland, and grassland, transforming the “carbon sink” into “carbon source” land, such as industrial land, dump, stripping land, and open pit. Furthermore, mining activities have caused serious damage to the ecological environment, reducing or even losing the carbon sink capacity of the ecosystem in the mining area, while the implementation of ecological restoration projects effectively improves the carbon sequestration capacity. The Pingshuo mining area has changed significantly from the construction of the mine in 1986 to 2018, and the land use conversion is obtained through ArcGIS software (Table 3).

From 1986 to 2018, the arable land in the Pingshuo mining area is converted into 14,085.34 ha, of which 30.4% is converted to grassland, and 25.9% is converted to forestland.

Table 2 Land use classification of open-pit coal mine based on remote sensing images

Land use type	Description
Arable land	Land that engages in agricultural activities to obtain food and products
Grassland	Land where herbaceous plants are grown
Forestland	Includes original forestland in the study area and dump site reclaimed as forestland
Urban land	Land for factories, houses, and parks in the city
Rural land	Land of the rural residence base
Transportation land	Land types such as ground lines and stations used for transportation
Stripping land	Area formed by peeling off the topsoil and rock covering the ore body
Opencast	Refers to the mining operation, the original landform is continuously cut in the vertical and horizontal directions, and finally a large pit of hundreds of meters to several kilometers is formed
Dump	Large piles formed by the waste generated during the mining process
Industrial land	Ground buildings, structures, and related facilities that serve the mine production system and auxiliary production systems
Water	Reservoir in the study area

The Loess Plateau exhibits severe soil erosion and is a key area for grain for the green in China. The Pingshuo mining area has continued to expand due to mining. Damaged land in industrial, open pit, stripping land, and dump land occupy 4482.5 ha of arable land, accounting for 31.8% of the arable land transferred. The amount of grassland converted is 6946.97 ha, of which 53.9% is converted to cultivated land and 19.8% to forestland. Industrial land, open pit, stripping land, and dump occupy 1648.13 ha of grassland, accounting for 23.7% of the grassland transferred. Forestland transferred out is 4211.57 ha, of which 53.6% is converted to arable land, and 17.5% was converted to grassland. Industrial land, open pit, stripping land, and dump land amount to 963.49 ha of forestland.

Open-pit mining must strip tens or even hundreds of meters of soil. The annual Loess stripping volume reaches 35–40 million m^3, and the stripped topsoil and rocks form a dump of a height of 150–190 m. Arable land, forestland, and grassland occupied by mining activities will produce 82.11, 92.67, and 88.35 t/ha soil carbon loss and 5, 15.5, and 6.398 t/ha vegetation carbon loss, respectively (Yang et al. 2019). Under the background of carbon peaking and carbon neutrality in the new era, green and low carbon mining is realized through technological innovation, which minimizes disturbance to the land under the condition of unchanged coal output, avoiding carbon losses, and achieving the goal of reducing emissions and increasing sinks.

3.3 Changes in carbon sink function areas

Using ArcGIS to process remote sensing images, the carbon sink function of the Pingshuo mining area from 1986 to 2018 is divided into four types: the carbon sink invariant area, carbon sink enhancement area, low carbon optimization area, and carbon emission control area (Fig. 4).

From 1986 to 2000, the carbon sink invariant area accounted for 66.7%, and was mainly concentrated in mining areas, and areas other than cities and towns. Among them, the carbon sink enhancement area accounted for 4.1%, which is mainly distributed in the reclaimed dumps in the mining area. During this period, the Pingshuo mining area completed the land reclamation of the Antaibao inner, south, and west dumps. The reclaimed areas were 560, 226.7, and 313.3 ha, respectively. The low carbon optimization area was 6.8%, distributed across transportation land, rural residential areas, and urban expansion. The carbon emission control area accounted for 4.2%, mainly from the damaged land produced by the Pingshuo Antaibao open-pit coal mining. During this period, only the Antaibao open-pit coalmine was put into operation. The land use type has not changed significantly, the urban expansion has not been evident, and the implementation of the land reclamation project has achieved initial results.

From 2000 to 2009, the carbon sink invariant area accounted for 48.8%. During this period, the Anjialing open-pit coalmine was operational. At the same time, rapid economic development led to high conversion rates of arable land, forestland, and grassland (conversion into open pits, dumps, stripping land and industrial land). The carbon sink invariant area decreased by 17.9% compared with the previous period. The carbon sink enhancement area accounted for 9.69%, which is approximately twice the proportion of the previous period. The Antaibao west dump expansion area, Antaibao erpu dump, Anjialing west dump, and Anjialing east dump began to be reclaimed, and the reclaimed areas were 560, 24.7, 117.3, and 196.3 ha, respectively. Simultaneously, the Loess Plateau became a key area of the Grain for Green project in China, and was also the main reason for the increase in carbon sinks. The low carbon optimization area accounted for 14.6%, mainly distributed in the mining periphery. The carbon emission control accounted for 5.5%, marking a slight increase from the previous period. This was mainly attributed to the operation of the Anjialing open-pit coalmine. Because of the mining and operation of two large open-pit coalmines in Antaibao and Anjialing, land use types have changed significantly, economic development was accompanied by urban expansion, and land reclamation has significantly improved the carbon sink function of the Pingshuo mining area.

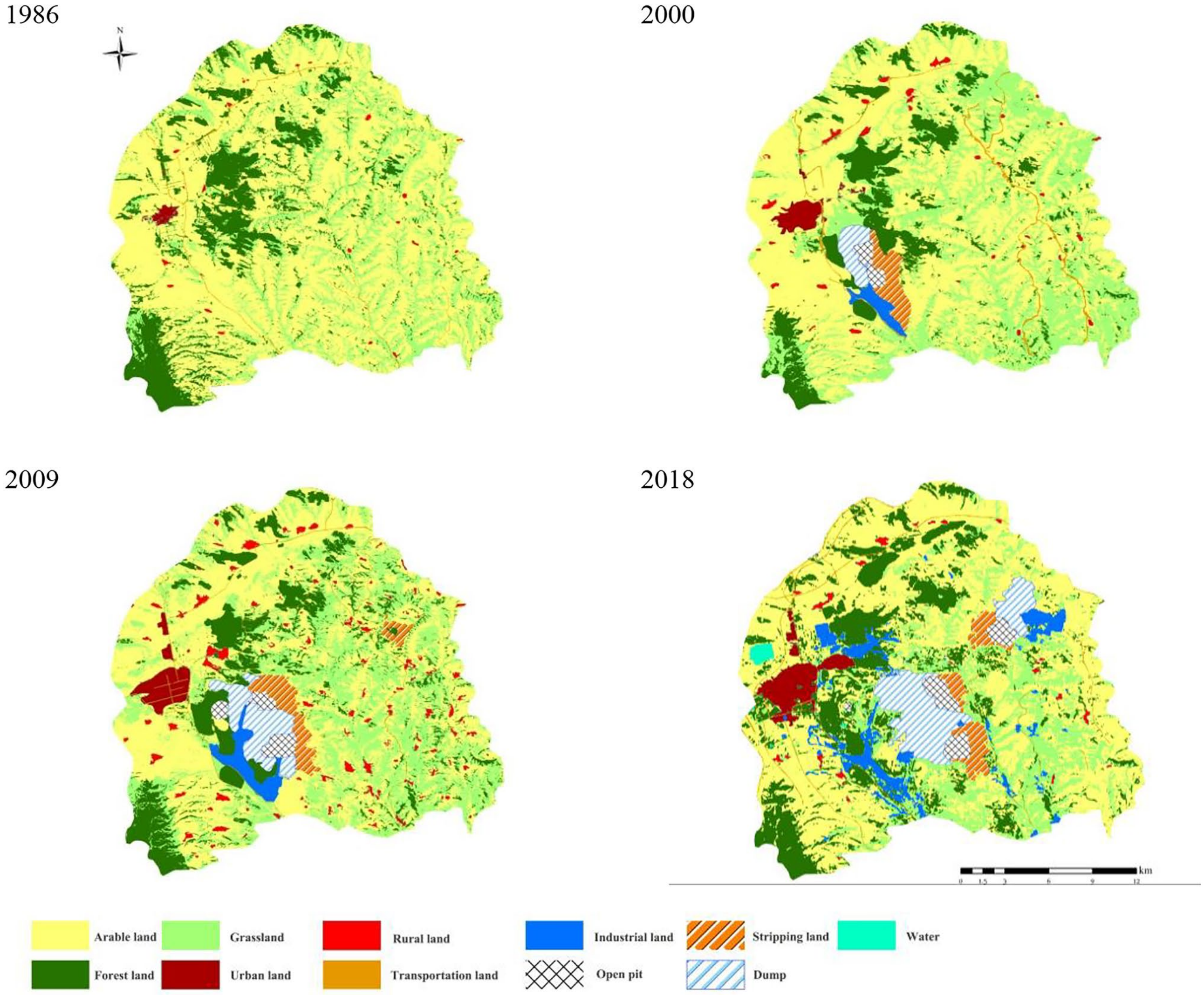

Fig. 2 Land use in Pingshuo mining area in 1986, 2000, 2009, and 2018

From 2009 to 2018, the carbon sink invariant area accounted for 42.7%. During this period, the Donglutian open-pit coal mine was put into operation, which was the main reason for the decrease in the stable carbon sink function area. The carbon sink enhancement area accounted for 14.8%, land reclamation began in the Anjialing inner dump, Donglutian north dump, papaya boundary, and completed land reclamation area of 354.7, 101.3, and 100 ha, respectively. The low carbon optimization area accounted for 15.7%. Although economic development continued to help the expansion of urban areas, the growth rate slowed down significantly. The carbon emission control area accounts for 8.2%, mainly due to the continuous expansion of mining areas. During this period, three large open-pit coalmines in Antaibao, Anjialing, and Donglutian were operated at the same time. The types of land use changed significantly, urban expansion had stabilized, and the effect of land reclamation was remarkable.

From 1986 to 2018, the carbon sink functional area of the Pingshuo mining area showed that the proportion of the carbon sink invariant area continued to decrease, while the carbon sink enhancement area and the low carbon optimization area gradually increased. The expansion of urban construction and mining areas encroached on a large amount of cultivated land, woodland, and grassland, which led to a decrease in areas with the carbon sink invariant area. The implementation of returning farmland to forests and grasslands and the land reclamation projects in the Loess Plateau are the main reasons behind the increasing trend of the carbon sink enhancement area. The low carbon optimization area is mainly attributed to the expansion of cities and the occupation of arable land, forestland, and grassland for

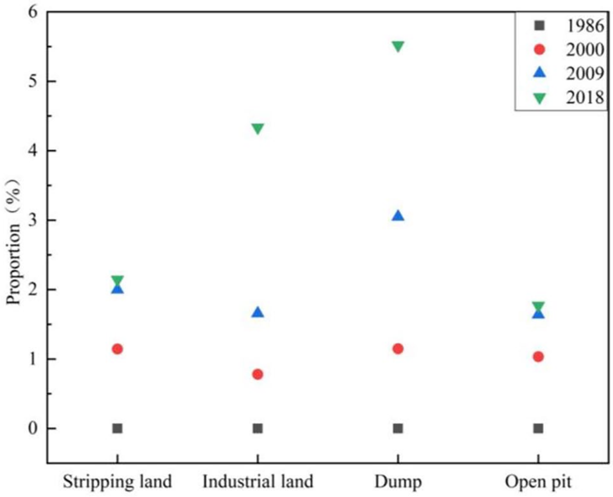

Fig. 3 Proportion of damaged land area

transportation due to economic development, the pressure on carbon emissions is relatively weak. Carbon emission control areas are mainly concentrated on damaged land in mining areas, which reduces the use of fossil fuels, controls the spontaneous combustion of coal gangue, and shortens transportation distances. Through the adoption of integrated technology, the reconstruction of landforms, soil reconstruction, vegetation reconstruction, landscape reappearance, biodiversity reorganization, and protection realizes the restoration of damaged land in mining areas. By 2016, 11 dumping areas have been reclaimed in the Pingshuo mining area, with a total area of 2340 ha, of which 1394 ha was reclaimed as forestland, and 946 ha was reclaimed as arable land.

4 Path to carbon neutrality

Neutralizing carbon in mining areas is difficult, and carbon emissions from mining activities as well as carbon losses from land use changes are significantly greater than carbon storage of land reclamation. However, the carbon sequestration capacity of reclaimed land in mining areas is positively correlated with reclamation years and exhibits a cumulative effect (Akala and Lal 2001; Yuan et al. 2016). According to the spatial layout and temporal changes of the carbon sink invariant area, carbon sink enhancement area, low carbon optimization area, and carbon emission control area in the Pingshuo mining area, mining activities must reduce the disturbance to the original landform by optimizing the mining and drainage plan and the design of the dumping land, such that the carbon sink invariant area can be maintained at a high level. The ecosystem of the Loess Plateau is fragile, and long-term monitoring and supervision of reclaimed land and the grain for green areas have continuously improved the carbon sink function. Several measures must be implemented in the carbon emission control area, such as selecting energy-saving equipment and eliminating outdated production capacity, to promote CO_2 emission reduction.

The reduction of carbon emission in mining areas must be considered in the whole process of “stripping-mining-transportation-dumping-reclamation” mining, which will be accompanied by carbon emissions by fuel use, explosion use, electricity use, coalbed methane, and spontaneous combustion (Fig. 5). In the process of stripping, land occupation must be reduced, damage to land must be minimized, and disturbance to vegetation and soil must be decreased. The strategy of “pumping before mining” for coalbed methane must be implemented to reduce the escape of methane gas in the mining process. Transportation and dumping must optimize the transportation distance, reduce fuel consumption, and timely and effectively reclaim damaged land after mining. The whole process of mineral resource development must strictly follow the 5R principle of “reduction, reuse, recycling, redevelopment, and restoration”, and optimize the structure, layout, mode and function of land use through ecological restoration in mining areas.

Table 3 Land use conversion from 1986 to 2018 (ha)

2018\1986	Arable land	Forestland	Grassland	Urban land	Rural land	Transportation land	Total
Arable land	18,033.20	2255.31	3746.07	0.47	86.15	70.13	24,191.34
Forestland	3644.16	4215.16	1372.83	0.63	14.15	53.37	9300.30
Grassland	4288.66	735.07	3708.57	1.62	14.10	45.34	8793.36
Urban land	916.36	156.90	65.51	171.25	3.92	4.83	1318.77
Rural land	218.53	11.20	28.23	0.09	24.90	1.01	283.95
Transportation land	356.09	77.22	80.33	0	0.52	25.28	539.45
Industrial land	1401.57	344.99	472.69	0.15	14.31	9.59	2243.29
Open pit	615.25	80.77	217.35	0	0	1.33	914.70
Stripping land	790.02	65.48	249.79	0	0	3.96	1109.25
Dump	1675.66	472.25	708.30	0	0.12	0	2856.33
Water	179.04	12.40	5.87	0	0	0	197.31
Total (ha)	32,118.54	8426.73	10,655.54	174.21	158.18	214.84	51,748.04

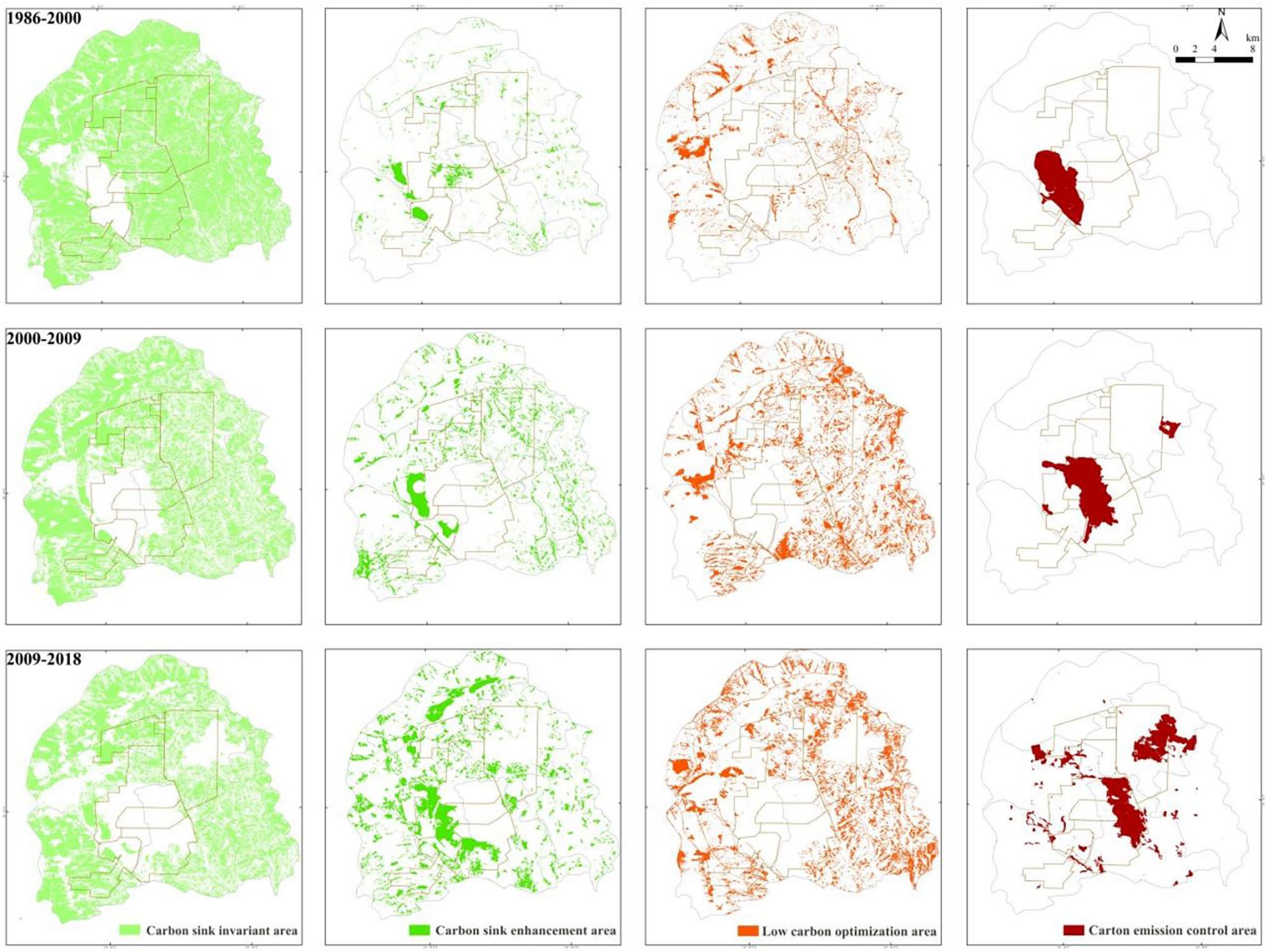

Fig. 4 Carbon functional areas in Pingshuo mining area from 1986 to 2018

Reduction forms the basis for achieving carbon neutrality in mining areas to reduce the use of fossil fuels and mining activities to disturb the ecological land, so as to maintain the carbon sink invariant area at a certain level. Reuse refers to the reclamation of damaged land in mining areas and the selection of reuse methods according to local conditions to enhance the carbon sink function of the ecosystem. The realization of carbon neutrality must make recycling, energy conservation, consumption reduction, and emission reduction projects in mining areas the goal in order to develop a circular economy. For example, the mining area must recover the washed coal slime and use coal gangue to generate electricity. Mining activities must be as intensive, meticulous, and multi-mining as possible, and ultimately achieve refined mining of resources, maximize waste utilization, and minimize environmental pollution. Corresponding measures must be taken to promote the redevelopment of land resources in mining areas, optimize land allocation, and increase land utilization and output rates, to achieve sustainable utilization goals. The restored land ecosystem in the mining area was shown to be better than the original landform after a long time of succession. In the future, social capital is encouraged to participate in ecological restoration projects to help achieve the goal of carbon neutrality.

Carbon neutrality in the coal industry will proceed through three periods, namely the peak period in 2020–2030, the breakthrough period in 2030–2050, and the neutral period in 2050–2060. In the next few years, coal will remain an important basic energy source in China, and it is necessary to replace coal resources with clean or renewable energy through technological innovation. At the same time, the carbon sink function of the mining area must be improved through ecological restoration projects. In the breakthrough period from 2030–2050, technical innovation is required, focusing on the research and development of low-carbon and green mining technologies in mining areas to achieve green, low-carbon, and clean production of the entire coal industry chain. The research and development of carbon capture technology must be strengthened to break through the new bottleneck of recycling technology using CO_2 as a

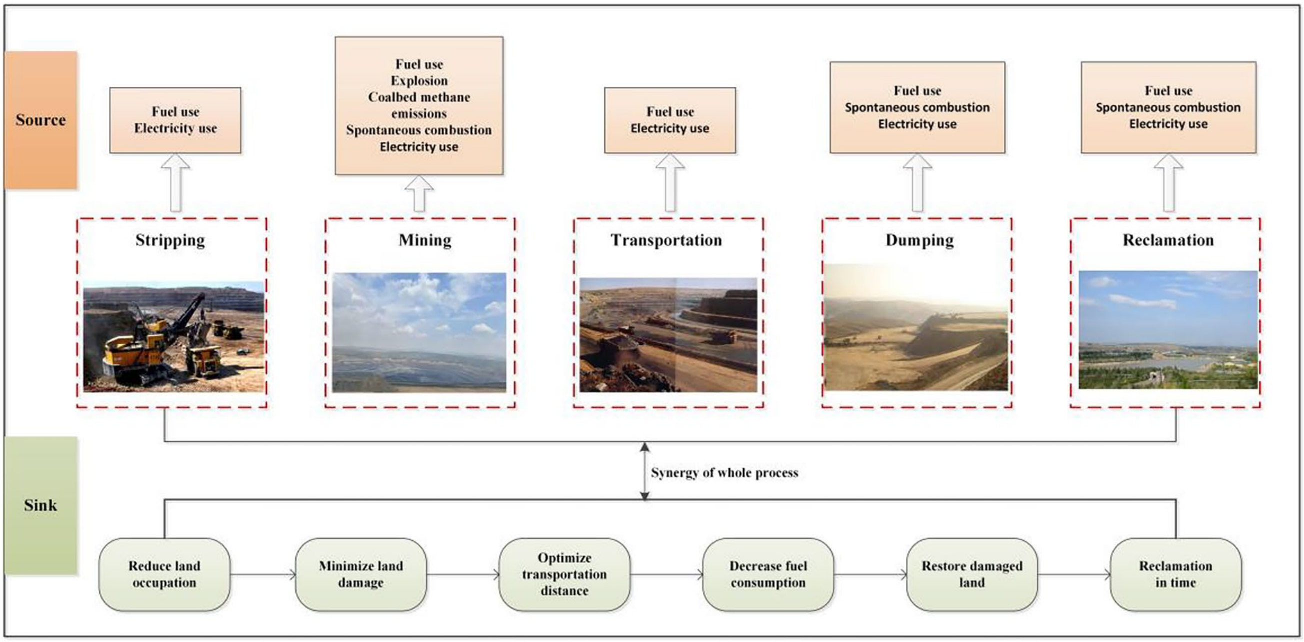

Fig. 5 Path to carbon neutrality in the mining area

raw material. In the carbon neutralization period from 2050 to 2060, coal resources are gradually being replaced, and the carbon sequestration benefits of land reclamation in mining areas are gradually prominent. It is necessary to achieve near-zero disturbance of the ecological environment caused by coal mining and to ensure the carbon sink function of the ecosystem with a new concept of ecological restoration. The development of mineral resources must realize the green prospecting, green mining, green utilization, and green restoration of the entire life cycle of "building-mining-transporting-utilization-closing-restoration".

5 Conclusions

Affected by the development of mineral resources and human activities, the Pingshuo mining area has undergone significant changes in land use over the past 30 years. Based on the land use data from 1986 to 2018, the ArcGIS software was used to obtain the land use transfer matrix and divide the carbon sink functional areas. Ecological restoration projects represent effective measures to improve the carbon sink function of mining areas, which is a long process. Carbon neutrality in mining areas must follow the 5R principles of "reduction, reuse, recycling, redevelopment, and restoration".

The land use types in the Pingshuo mining area are mainly arable land, forestland, and grassland. From 1986 to 2018, the arable land areas showed a decreasing trend, the forestland was first decreasing and then increasing, and the grassland decreased with fluctuations. The main reason behind these trends is that the damaged land proportion in the mining area has grown rapidly, starting from zero. Since 2018, the stripping area, industrial land, dump, and open pit in the Pingshuo mining area accounted for 1109.25, 2243.29, 2856.33, and 914.7 ha, respectively. From 1986 to 2018 in the Pingshuo mining area, arable land, forestland, and grassland were transferred out of 1408.34, 421.57, and 6946.97 ha, respectively. Among them, 31.82% of industrial land, open pits, stripping land, and dumping areas are from arable land, 22.88% from forestland, and 23.72% from grassland. With the background of carbon peaking and neutrality in the new era, green and low-carbon mining is realized through technological innovation, which minimizes disturbance to the land under the condition of unchanged coal output. Carbon sink invariant areas are concentrated outside of mining areas and towns, and reduced from 66.7% to 42.7%. Carbon sink enhancement areas are concentrated in the reclaimed land and the grain for the green area, increasing from 4.1% to 14.8%. The low carbon optimization area and the carbon emission control area have shown an increasing trend, mainly concentrated in towns and mining operation areas. The carbon-neutral path of the mining area must start from the full life cycle of coal resources "building-mining-transporting-utilization-closing-restoration," and reduce emissions from the entire mining process of "stripping-mining-transportation-dumping-reclamation".

Coal resources are a long-term basic energy source, constituting a relatively large proportion of primary energy sources, and the energy transition has a long path ahead. Carbon neutrality in the coal industry involves multiple fields, such as mining, ecology, and chemical engineering. It requires multidisciplinary integration and relies on technological innovation to promote carbon neutrality in mining areas. A scientific and reasonable transformation plan must be urgently formulated to ensure the economic safety of practitioners in various industries. Ecological restoration is an effective method to help mining areas achieve carbon neutrality, albeit being a long-term and complex process. Only by scientific management of mining areas can we truly achieve the goal of ecosystem restoration and ensure sustainable development of the ecosystem.

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Authors' contributions YANG Boyu: Conceptualization, methodology, investigation, writing of original draft. BAI Zhongke provided framework of manuscript, FU Shuai performed data processing, and CAO Yingui provided basic data.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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