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Impact and elastic modulus of coal mining on terrestrial ecosystems

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The energy consumption structure is gradually evolving into a "diversified energy structure" against the backdrop of the global implementation of energy-saving and low-carbon policies. Coal, as the main energy source in China, is difficult to change in the short term, given the characteristics of China's energy and resource endowments, as well as the actual social and economic development at the present stage. Nevertheless, coal mining inevitably leads to a range of ecological issues. Identifying the impact of coal mining on terrestrial ecosystems and adopting resilient recovery measures are crucial prerequisites for advancing green coal mining efforts and attaining carbon peaking and carbon neutrality goals. Using China's open-pit coal mining as a case study: (1) the research examines the fundamental attributes and evolving patterns of spatial distribution among these mines within the country. Furthermore, it delineates the life cycle stages and distinctive features of the five principal open-pit coal mines. The life cycle of a coal mining area is divided into four distinct development phases: the initial phase, the accelerated phase, the stable phase, and the declining phase. The spatial relationship between the life cycle stages of coal mining and ecosystem succession is elucidated by examining the evolutionary types of ecosystems within coal mine area. In the accelerated and stable development phase, the adverse effects of coal mining on the ecosystem are in a long-term increasing trend, causing the key elements of the ecosystem to gradually surpass their threshold values. The ecosystem is out of balance, severely damaged, and gradually undergoing degradation or extreme degradation. The types of ecological succession in coal mining areas can be categorized as follows: terrestrial succession leading to a new terrestrial ecosystem, terrestrial to aquatic ecosystem transitions, or the development of an amphibious symbiotic ecosystem. (2) The research quantitatively assessed the impact of surface coal mining on terrestrial ecosystems by utilizing remote sensing data in conjunction with coal production information. In 2022, the affected areas of the five major open-pit coal mines due to coal mining activities amounted to approximately 0.02% of China's total land area. Meanwhile, the nationwide affected areas of all open-pit coal mines combined reached to approximately 0.13% of China's land area. Open-pit coal mining activities have a significant impact on the surface. (3) By incorporating the ecological resilience theory, we establish a model for the ecosystem's elastic modulus in coal mining areas, taking into account landscape diversity, vegetation coverage, land type, and climate factors, which are based on the concepts of elastic strength and elastic limit. A conceptual model for recognizing ecological thresholds in coal mining areas is developed by incorporating the comprehensive integrity index of the ecosystem. The comprehensive integrity of the ecosystem within a coal mining area undergoes significant alterations as it crosses three distinct ecological thresholds: the elastic point, the yield point, and the mutational point. There should be a corresponding constant (or constant interval) at the three ecological thresholds of ecosystem resilience, the elastic point, the yield point, and the mutational point, which is closely related to the scale of mining operations, mining technology, and the service life in coal mining areas. The established models for identifying ecological thresholds and the resilience modulus degree serve as both theoretical references and practical bases for managing the progress and trends of ecosystem changes during coal resource extraction, making ecological restoration in coal mine areas more target-oriented and specific.

Keywords Coal mining, Terrestrial ecosystem, Life cycle, Ecosystem succession, Elastic modulus

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Coal resources are vital foundational energy sources and raw materials for human sustenance, providing the backbone for the rapid industrialization worldwide[1,2]. In China, coal serves as the predominant energy source, with its proven reserves constituting approximately 96% of the country's fossil fuel reserves. For an extended period, it has held over 50% of the share in the primary energy consumption mix. According to the Chinese Academy of Engineering, coal resources are projected to constitute approximately 40% of China's primary energy consumption by 2050[3]. In the process of ensuring a basic energy supply and promoting social and economic development, the exploitation and utilization of coal resources inevitably have adverse effects on the ecological environment, including disturbances to geological and geomorphic features, damage to natural landscapes, reductions in biodiversity, and land degradation[4–7]. The disturbance to the ecological environment caused by coal resource mining may initially appear localized to the mining points. However, when considering the involvement of waste discharge in the geochemical cycle, the scope of ecological damage can easily extend beyond these points, spreading along lines, across planes, and through networks. This can lead to regional, and potentially even global, ecological environmental issues[8,9]. Furthermore, the finite reserves of coal resources, coupled with excessive mining that has led to overcapacity, have resulted in extensive and inefficient extraction practices. Such practices are more likely to exacerbate the waste of coal resources and cause damage to the ecological environment. To some extent, this has hindered the high-quality and sustainable development of human society. It is imperative to clarify the impacts of coal mining activities on the ecosystem, reveal the ecological evolution process in coal mining areas, and strike a balance between the exploitation and utilization of coal resources and the protection and rehabilitation of the ecological environment.

Scholars at home and abroad have introduced the resilience theory to the coal mining coal and have conducted substantial research and practical innovations in the realms of ecological resilience, ecological thresholds, and adaptive cycles[10,11]. Ecological resilience refers to the capability of an ecosystem to sustain its essential characteristics in the face of disturbances caused by external forces. This concept holds significant importance for assessing regional ecosystem security and implementing regulatory measures[12,13]. Ecological resilience is defined as the capacity of an ecosystem to absorb disturbances through adjustments in parameters like state variables and driving variables, while maintaining its structural integrity and functional feedback mechanisms[14–16]. Ecosystems tend to recover more readily when subjected to fewer disturbances from external forces. When external disturbances to an ecosystem approach or exceed its ecological threshold, they can cause the system to deviate from its equilibrium state and transition into a new one. This shift may ultimately result in the impairment and deterioration of the ecosystem[15]. Applying ecological resilience thinking in managing the mining area ecosystems is an effective approach to reversing the degradation of the mining area's ecological environment[17]. Bian emphasized that when studying ecological issues in reclaimed areas, it is crucial to consider ecosystem resilience, which is reflected by the time required for the system to return to its equilibrium state following a disturbance[18]. Joseph et al. emphasize that managing the ecological vulnerability induced by mining disturbances requires a focus on resilience to ensure the sustainable development of socio-ecological systems within mining areas[19]. Research on ecosystem resilience in mining areas primarily concentrates on the measurement of ecosystem resilience[20,21], health evaluation[22,23], institutional changes[24], and vegetation restoration[25]. Among these, the measurement of ecosystem resilience is vital for predicting ecosystem changes and safeguarding and regulating the ecological environment[26]. At present, there are mainly three methods to measure the mining ecosystem resilience: (1) calculating the area of each land use type and applying its respective elasticity value, and land use types in coal mining areas are typically classified using deep learning algorithms such as Deep Convolutional Neural Networks (DCNNs) based on multi-source remote sensing data[27–31]; (2) calculating the landscape diversity index, vegetation index, and regional average annual temperature and precipitation from the perspective of landscape patterns; (3) identifying the fundamental characteristic elements of an ecosystem, including climate, biology, topography, and geomorphology, and constructing a comprehensive measurement index system, which takes into account weighted calculations. Selecting the key factors affecting ecosystem resilience and constructing an index system for comprehensive evaluation is a common approach employed in contemporary empirical research. Typically, current research methodologies predominantly focus on a regional scale, often lacking in comprehensive consideration of relevant factors. Moreover, they do not adequately address the variations in ecological resilience within mining ecosystems across various stages of mining operations. The scientific measurement of mining ecosystem resilience across various stages remains a challenge due to the lack of a theoretical framework and reference cases for applying effective modeling methods and technical tools.

The research elucidated the stages of the coal mining life cycle and the process of ecological succession in areas affected by resource extraction, revealing the correlations between the stages of coal mining and the progression of ecosystem succession. Using China's open-pit coal mines as a case study, the life cycles and distinct stages of five such mines were elucidated. The quantitative assessment of the environmental impact of open-pit coal mining on terrestrial ecosystems was conducted, utilizing both image data and coal production records. By integrating the theory of ecological elasticity with the life cycle stages of coal mining and the process of ecosystem succession, models such as the ecosystem elasticity modulus for coal mining areas and conceptual frameworks for recognizing ecological thresholds have been developed. These tools are designed to ascertain the trajectory and direction of ecosystem evolution within coal mining areas and offer a scientific theoretical foundation for the ecological rehabilitation efforts in these areas.

Global coal exploitation

Coal reserves and consumption distribution

According to the 2023 Statistical Yearbook of World Energy released by the Energy Institute (EI), coal consumption experienced a 0.6% increase in 2022, reaching its highest level since 2014. In the short term, coal continues to hold a significant place in the global energy consumption structure. According to the "Energy

Institute Statistical Review of World Energy 2023" report, as of the end of 2020, the world's proven reserves of coal resources at 1,074.108 billion tons. From a regional perspective, the distribution of global proved coal reserves is uneven. Among these regions, Asia–Pacific, North America, the Commonwealth of Independent States, and Europe are the primary areas where coal resources are distributed, accounting for 97.23% of the world's proven coal reserves. Specifically, China has the fourth largest proven coal reserves globally, at 143.197 billion tons, which represents 13.33% of the world's total proven coal reserves. The proven reserves of coal resources in the Middle East, Africa, Central and South America, and other regions are relatively scarce, accounting for only 2.77% of the world's total proven coal reserves (Fig. 1).

The evolution of the global coal consumption pattern is intrinsically linked to both the progress of worldwide economic development and the varying levels of economic advancement across nations. Since the 1960s, the global consumption of coal resources has exhibited a significant upward trend, rising from 581.0 terajoules in 1965 to 1614.7 terajoules in 2022. Between 2012 and 2022, the total global coal consumption experienced a modest increase of 1.89%, reflecting a gradual shift towards a "diversified energy structure" as the world moves towards energy conservation and low-carbon policies. The distribution of global coal resource consumption is unevenly distributed, with the majority concentrated in the Asia–Pacific, North America and Europe also contribute significantly to global coal consumption, together accounting for 93.57% of the global total. In Asia–Pacific, China alone accounts for 54.75% of global coal consumption, making it the largest coal consumer in the world. The Asia–Pacific region holds a significant position in global coal consumption, accounting for 80.82%, thereby dominating the worldwide coal usage landscape (Fig. 2).

History of coal resources development

The evolution of coal resource development globally can be categorized into five distinct stages. The early stage of coal resource development (before the 1760s), the birth and development of the coal industry (from the 1760s to the early nineteenth century), the boom period of the coal industry (from the mid-late nineteenth century to the mid-twentieth century), the depression period of the coal industry (from 1950 to 1973) and the redevelopment period of the coal industry (from 1973 to the present). The earliest human understanding of coal resources dates back to BC. China is among the earliest countries to have recognized, exploited, and utilized coal resources. In the years leading up to the 1760s, due to the constraints of productivity, coal resources were not extensively exploited and utilized. At that time, firewood remained the primary source of energy. Since the eighteenth century, coal has become the main energy source for industry and transportation in Western countries. By the late eighteenth century, with the onset of the Industrial Revolution, coal emerged as the primary driver of industrialization in Europe and later in the United States. The invention and widespread adoption of the steam engine, along with advancements in the metallurgical and transportation industries, established the pivotal role of coal as the primary source of global energy. In the mid-nineteenth century, the steel industry flourished, and the Western industrial countries ushered in the "steelmaking era". As energy consumption grew and industrial transformations took place, the coal industry experienced a period of prosperity in the early twentieth century. In 1913, the output of coal resources accounted for 92.20% of the world's total primary energy production. After the 1920s, the world energy structure has undergone great changes, oil and natural gas have become one of the main energy sources in the world, and the main energy status of coal resources has been declining. During the golden age of oil, spanning from 1950 to 1973, the coal industry experienced slow development and entered a period of depression, with coal production increasing by just 12.20% during this time. In the 1970s, the oil crisis brought the coal industry back to life, the production of coal resources accelerated growth, and the production

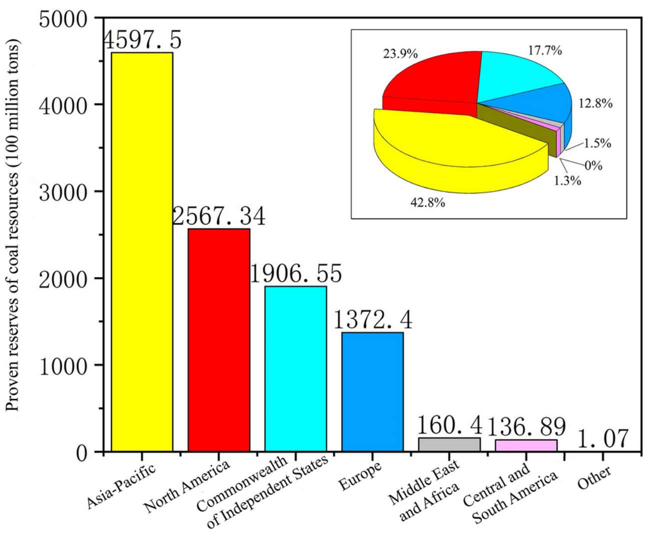


Fig. 1. Distribution of proven reserves of coal resources in 2022. The bar chart shows the proven coal reserves (100 million tons) in various regions around the world in 2022, while the pie chart shows the proportion (%) of the proven coal reserves.

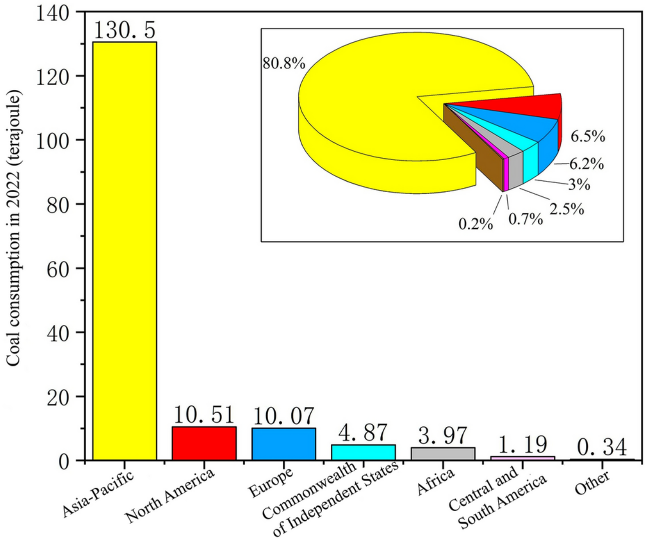


Fig. 2. Global distribution of coal consumption in 2022. The bar chart shows the coal consumption (terajoule) in various regions around the world in 2022, while the pie chart shows the proportion (%) of the coal consumption.

and utilization were greatly developed. After the 1990s, the coal industry underwent continuous transformation and upgrading, with its development increasingly moving towards intensification, informatization, and globalization. According to the forecast of the world's major energy institutions, the proportion of coal, oil and natural gas in the world's primary energy consumption will remain at about 30% in the foreseeable future for a long time, which is the most important main energy in the energy field.

Impact of coal resources exploitation on ecological environment

The exploitation and utilization of coal resources not only contribute to the development of human society and the growth of the national economy but also have a significant negative impact on the ecological environment, which is primarily manifested in both direct and indirect damages. The mining technology of coal resources mainly includes open-pit mining and underground mining. Open-pit mining is suitable for conditions where ore deposits have a large thickness and are shallowly buried. It is a mining method used to access coal resources by directly removing the overlying soil and rock that cover the ore body. The main impacts on the ecological environment include air pollution, water pollution[32–34], land degradation and contamination, as well as triggered geological disasters[35,36]. Underground mining is suitable for conditions where deposits are deeply buried. It is characterized by underground operations, multiple production stages, and intricate processes. The production site continuously shifts as coal resources are extracted. The impacts on the ecological environment include air pollution, mining wastewater pollution, induced geological disasters, and mine thermal pollution[37–39]. Table 1 illustrates the forms and characteristics of the impacts resulting from coal resource exploitation on the ecological environment.

Coal mine life cycle and ecosystem succession

Life cycle stage of coal mine

The life cycle of a coal mine can be divided into seven periods: the planning period, the construction period, the put into production period, the reach production period, the stable production period, the decline period, and the replacement closing period. According to the development characteristics of coal mining area in each period, the life cycle stages of coal mining area can be summarized as the initial development stage (the planning period and the construction period), the accelerated development stage (the put into production period and the reach production period), the stable development stage (the stable production period) and the decline development stage (the replacement closing period). Coal mining areas at various life cycle stages exhibit distinct focuses in production organization, unique characteristics in coal resource development, and varying levels of population agglomeration. Furthermore, they exert differing forms, scopes, and degrees of impact on the resources and environment within these mining areas. This analysis examines the distinct characteristics of production scale, population demographics, damage severity, and industrial composition across various life cycle stages within coal mining areas. The characteristics of resource exploitation, along with typical resource and environmental problems and their explanations, are depicted in Fig. 3 (*t* represents the time, *Q* represents the total production of coal resources in a certain period, and *P* represents the production rate).

(1) The initial development stage is dedicated to the preparatory work and construction of essential facilities and equipment, including production systems. According to the phased development plan and deployment, preparatory work and construction activities are primarily focused on a few coal fields within the mining area. The scale of mining is relatively small, with the population gradually congregating in the mining zone.

Mining technology	Types	Forms	Details
Open-pit mining	Direct damage	Digging and damaging land	The construction of open-pit mines, along with the final excavation belt conveyor, intercepting ditches, and other related excavations, leads to the removal of land and damages vegetation
		Occupying land	Coal waste, fly ash, mining buildings, structures, and roadways exert continuous pressure on the land, damaging surface vegetation
		Changing hydrogeological conditions, polluting land, air, water and so on	Land dredging, surface subsidence, erosion, and soil heavy metal pollution are among the environmental challenges we face. These issues can lead to the acidification of surface and groundwater. Furthermore, problems associated with erosion rock dumps, dump dust, spontaneous combustion of rock dumps, gas emissions and dust pollution during blasting, exhaust gas pollution from perforation, transportation, and other operations also contribute to environmental degradation
	Indirect damage	Inducing geological disaster	Slope, landslide, collapse, etc.
		Seismic wave shock	Seismic and shock waves can destroy both artificial structures and natural features, causing damage to buildings and other constructions during blasting operations
		Noise pollution	Noise pollution, resulting from blasting and various industrial operations, can adversely affect the hearing and overall health of residents in surrounding areas
Underground mining	Direct damage	Ground settlement	Underground mining leads to the movement and deformation of surface rock strata, resulting in ground subsidence, which can be divided into surface seepage subsidence, no surface seepage subsidence and so on
		Occupying land	Waste dumps, buildings, structures, engineering pipelines, highways, and other infrastructures exert pressure on the land, damaging surface vegetation
		Changing hydrogeological conditions, polluting land, air, water and so on	Land dredging, surface subsidence, and heavy metal pollution in soils are among the environmental issues faced. When surface water and groundwater flow into mines, they cause changes in the water table levels and lead to the acidification of both surface water and groundwater, resulting in water pollution within the mining areas. The leachate from these processes further contaminates surrounding water bodies and soils. Additionally, dust from dumps, as well as emissions from transportation and other operational activities, contribute to air pollution
	Indirect damage	Inducing geological disaster	Ground cracks, debris flows, collapses, etc.
		Noise pollution	Noise pollution generated by both surface and underground operations adversely affects the hearing and overall health of residents in the surrounding areas

Table 1. Impact of coal resources exploitation on the ecological environment.

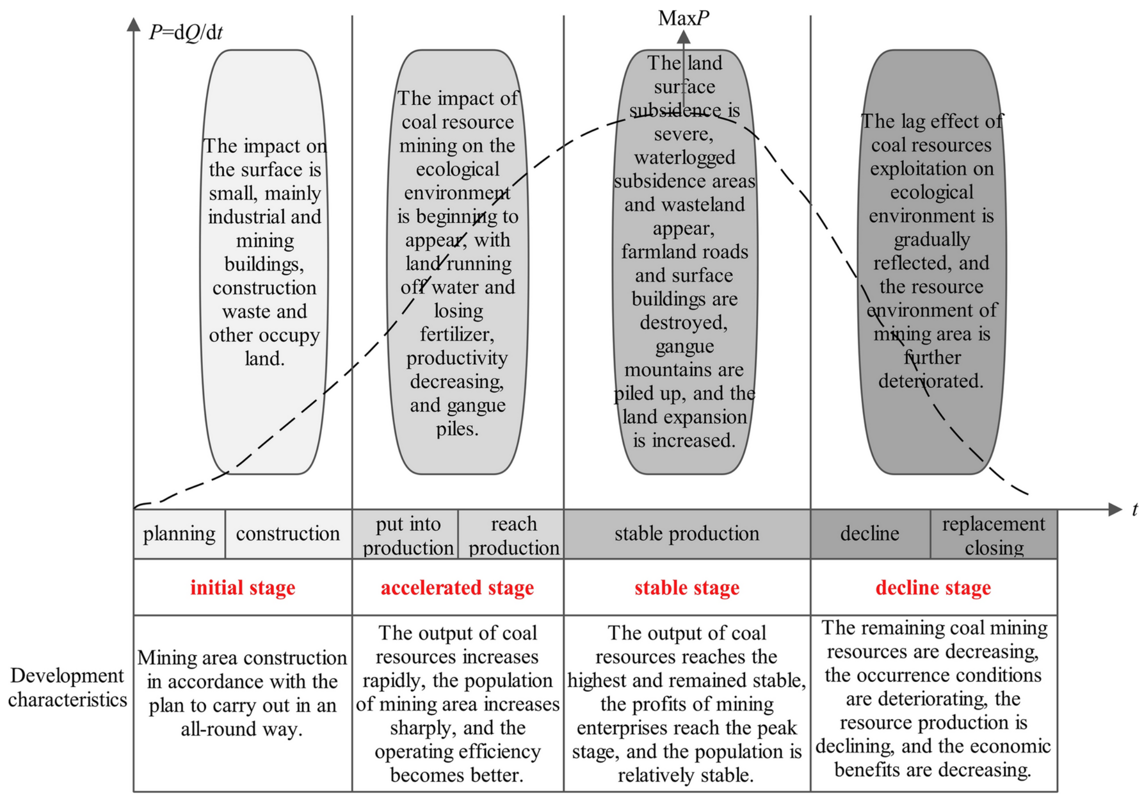


Fig. 3. Characteristics of resource exploitation and ecological environment in different life cycle stages of coal mine area.

Relevant supporting enterprises have not yet been established. The impact on resources and the environment is mainly manifested in the occupation of ecological space by industrial and mining structures as well as construction waste, and this impact is relatively minor.

(2) In the accelerated development stage, the output and mining scale of coal mining areas have been progressively expanding. As a result, an industrial chain centered on coal mining and washing has gradually taken shape, leading to a sharp increase in the population of mining areas within a short period. The impact of coal resource extraction on the resources and environment of mining areas is growing, with key manifestations including surface land destruction, soil pollution, declining land fertility and vegetation productivity, increased occupation of land by waste piles such as gangue and fly ash, significant emissions of gases, and a marked reduction in the quality of resources and the environment in these areas.

(3) In the stable development stage, the coal reserves in the mining area have reached their peak and are now stable, with the mining scale remaining largely unchanged. The industrial chain with coal mining as the core continues to extend, and coal mining has become the most important pillar industry in the mining area. The population in the mining area is relatively stable and mainly grows naturally, and the proportion of the elderly and minors increases. The intensity of mining activities has continued to rise, resulting in severe surface subsidence. This has led to instances of water subsidence and the creation of wastelands. High-grade highways have been affected to a certain degree, while field roads have suffered significant damage. Surface construction structures have also been compromised. Moreover, the land area occupied by coal gangue, fly ash, and other such accumulations has further expanded.

(4) In the decline development stage, the output of coal resources in the mining area is gradually diminishing, leading to a corresponding decrease in the proportion of the mining industry that is centered around coal extraction. If the reasonable adjustment and transformation of the industrial structure are not realized in time, the social and economic development of the mining area will decline, and a large number of people in the mining area will move out. However, due to the accumulated and lingering effects of resource depletion and environmental degradation, the impact of coal mining on the resources and environment within mining areas has not diminished. The socio-economic decline of these areas hinders their ability to invest in environmental remediation, leading to increasingly severe resource and environmental issues in mining area.

Ecosystem succession in coal mining area

Ecosystem succession in coal mining area refers to the sequential process in which the original ecosystem is disturbed and replaced by another ecosystem with the passage of time and the development of coal resources. The direction of ecological succession in a coal mining area is primarily influenced by the type of the original ecosystem prior to mining, the geographic location of the mining site, and the prevailing climatic conditions. The pre-mining ecosystem types can generally be categorized into natural ecosystems and artificial ecosystems. Natural ecosystems are further divided into aquatic ecosystems and terrestrial ecosystems. Artificial ecosystems include farmland ecosystems, urban ecosystems, and others. Mining areas located in arid and semi-arid areas are short of water resources, and their ecosystems are extremely fragile. Coal mining is very easy to cause soil erosion, land desertification, etc. The original ecosystems of mining areas, which include grasslands, deserts and semi-deserts, as well as the Loess Plateau, typically evolve into systems characterized by severe or extreme desertification. The loess mining area is situated in the upper reaches of the Yellow River basin, where the ecological environment is fragile. The landform and geological mining conditions are complex, characterized by a substantial thickness of the loess layer, rapid surface subsidence, a short starting distance, and severe instances of mining fractures and other forms of discontinuous failures. The mining area situated in humid and semi-humid regions features flat terrain with a high water table. Extracting groundwater through mining activities can alter the existing terrestrial ecosystems (such as farmland, forests, grasslands, cities, etc.), potentially leading to the emergence of aquatic ecosystems or amphibious symbiotic systems. The succession types of a mining area ecosystem can be categorized as terrestrial succession leading to a new terrestrial ecosystem, terrestrial to aquatic ecosystem transitions, or the development of an amphibious symbiotic ecosystem (Fig. 4).

Correlation analysis of life cycle stage and ecosystem succession in coal mining area

The succession process within an ecosystem in a coal mining area is closely linked to the stages of its life cycle. With the continuous development of coal resource exploitation activities, the ecosystem in the coal mining area will successively evolve into primitive ecosystem, damaged ecosystem, degraded or extremely degraded ecosystem, rebuilt/restored ecosystem and stable ecosystem (Fig. 5). Among these, a degraded ecosystem is one that requires artificial restoration intervention because it suffers irreversible damage and is difficult to recover from external disturbances. An ecosystem is said to be severely degraded if it experiences abrupt and significant changes as a result of internal interactions, environmental changes, or external disruptions. It is vital to use artificial techniques to repair the ecosystem's structure and function because they have been badly damaged. In the initial development stage of coal mining area, the construction of production and living infrastructure leads to the generation of solid waste in the mining area. The land has been primarily damaged and occupied through excavation, leading to the destruction of vegetation and the migration of species. However, there has been no significant ecological succession within the original ecosystem. In the accelerated development stage, with the continuous increase in coal resource exploitation and the expansion of the industrial chain, including coal transportation, washing, and processing, critical ecological elements such as water, land, and wildlife are being impacted. Large areas of the original landscape have been damaged, with underground rocks becoming fragmented. Industrial wastewater from selection and washing processes, along with domestic sewage, is being discharged. Additionally, activities such as blasting and gas leaks cause air pollution. The stability of the original

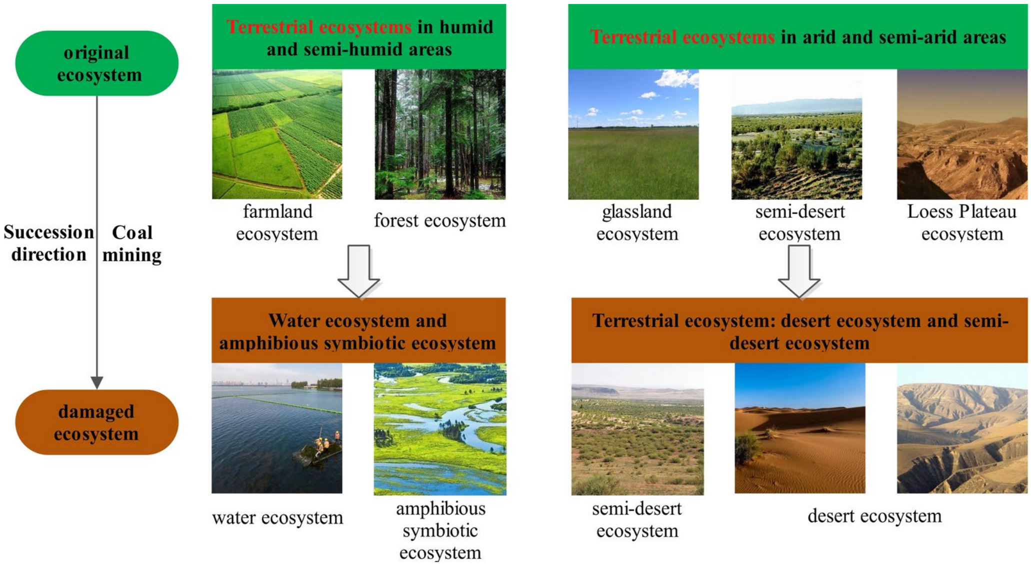


Fig. 4. Succession types of mining area ecosystem.

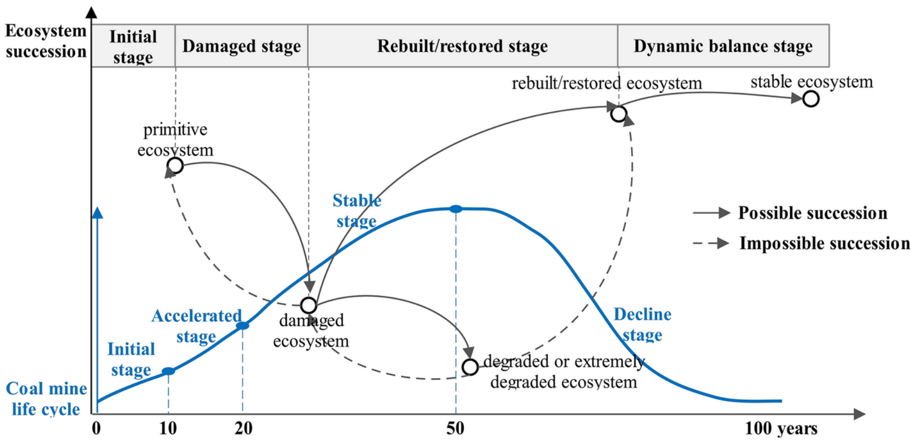


Fig. 5. Life cycle stages and ecosystem succession in coal mine area.

ecosystem has been compromised, and its carrying capacity is nearing the threshold. As a result, it is transitioning into a state of damage.

In the stable development stage, the mining amount in a coal mining area reaches its peak and stabilizes, the detrimental effects of mining activities on the ecosystem continue to grow. Key elements within the ecosystem gradually surpass their thresholds, leading to severe impairment and imbalance in ecosystem functions. Consequently, the ecosystem may transition into a degraded or severely degraded state. In the decline development stage, the mining area is facing the transition towards mine closure, with the extraction of coal resources gradually diminishing until the point of complete cessation. According to whether ecological restoration/reconstruction is carried out, the succession of mining ecosystem can be divided into two situations: (1) if no restoration measures are implemented, the mining ecosystem will continue to experience reverse succession as its structure and functions gradually deteriorate. Ultimately, this could lead to the formation of a severely degraded or even entirely degraded ecosystem, where both structure and function are completely lost. (2) When ecological restoration is implemented in a mining area, the ecosystem within the mining area will experience gradual positive succession. Its structure and functions will progressively recover, ultimately leading to the formation of a rational ecosystem characterized by a well-balanced structure, efficient functioning, and a relatively stable state of development.

Spatial characteristics of open-pit coal mines and their impacts on ecosystem in China

Development history and distribution of open-pit coal mine in China

China's development of open-pit coal mines primarily took place after the establishment of the People's Republic of China. In the 1950s, the Fuxin Haizhou open-pit coal mine was constructed in China, while the Fushun West open-pit coal mine and the Fuxin Xinqiu open-pit coal mine underwent reconstruction and expansion. From the late 1950s to the early 1960s, China constructed several major state-owned open-pit coal mines, including Pingzhuang West, Hegang Linguae North, Jalainur Lingquan, Hami Sandaoling, Shihuijing Dafeng, Yima North, and Tongchuan Jiaoping, as well as local state-owned open-pit coal mines like Xiaolongtan, Kebao, and Lvhe. By 1965, the production volume of open-pit coal mines in China had amounted to 4.351 million tons, representing 1.88% of the nation's overall coal production. From the late 1960s to the 1970s, China built Haibowan Wusu open-pit coal mine (national key coal mine) and Yunnan Xianfeng, Heilongjiang Yilan, Songjitun and other open-pit coal mines (national local coal mines). By 1980, the production volume of the state's key open-pit coal mines was 14.030 million tons, accounting for 4.07% of the country's total coal production. In 1981, the Coal Ministry put forth the development of open-pit coal mines as a strategic policy to advance the coal industry. Under the guidance of "giving priority to the development of open-pit coal mines" and "opening large open-pit as soon as possible", decisions were made to speed up the development of five open-pit coal mines, such as Huolinhe, Yimin, Yuanbaoshan, Jungar and Pingshuo.

The distribution of open-pit coal mines in China is obviously regional, mostly concentrated in the central and western regions. By 2022, there are 357 open-pit coal mines in China, including 245 in Inner Mongolia, 40 in Yunnan, 30 in Shanxi, 30 in Xinjiang, 1 in Guangxi, 1 in Hebei, and 10 in other provinces, as shown in Fig. 6.

Inner Mongolia, Yunnan, Shanxi, Xinjiang, and other major coal-producing regions predominantly serve as coal resource export areas, with relatively low levels of self-consumption. Coupled with inadequate transportation infrastructure, large-scale open-pit mining operations are constrained. In the meantime, the ecosystem in these areas is relatively delicate, and large-scale open-pit mining can lead to severe harm to the ecological environment. There are two main issues at play: firstly, the difficulty of ecological restoration; secondly, the destruction of surface vegetation exacerbates the occurrence of sandstorms, which directly impacts the central and eastern regions of China. Therefore, the scale of open-pit coal mining in China is relatively small, with the top five such

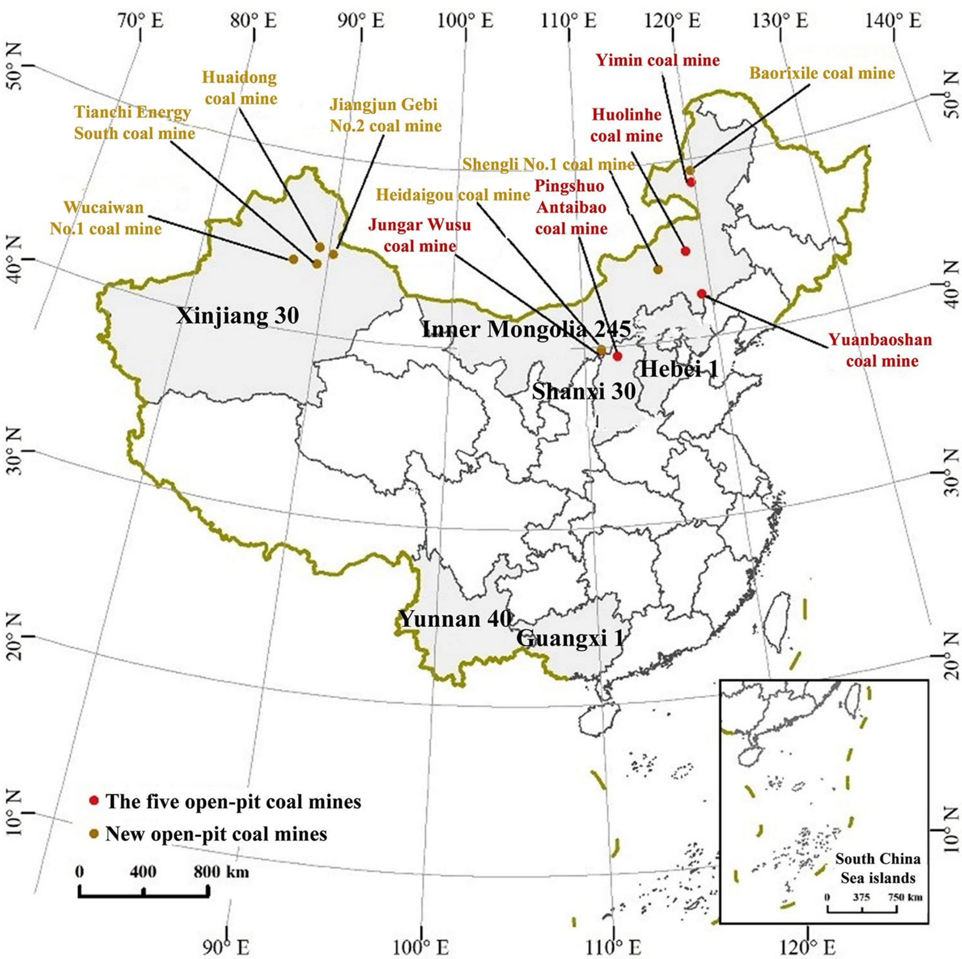


Fig. 6. Distribution of the open coal mine in China.

mines being the Huolinhe Open-pit Coal Mine, Yimin Open-pit Coal Mine, Yuanbaoshan Open-pit Coal Mine, Jinggar Wusu Open-pit Coal Mine, all located in Inner Mongolia, and the Pingshuo Antaibao Open-pit Coal Mine in Shanxi Province.

Life cycle and ecosystem succession process of the five open-pit coal mines

The main five open-pit coal mines in China are Inner Mongolia Huolinhe open-pit coal mine, Inner Mongolia Yimin open-pit coal mine, Inner Mongolia Yuanbaoshan open-pit coal mine, Inner Mongolia Jungar Wusu open-pit coal mine and Shanxi Pingshuo Antaibao open-pit coal mine. According to the theory of coal mine life cycle stages and ecosystem succession, the life cycle stages and ecosystem succession processes of the five major open-pit coal mines in China have been determined as outlined in Table 2. Inner Mongolia's Huolinhe Open-Pit Coal Mine, Yimin Open-Pit Coal Mine, and Shanxi's Pingshuo Antaibao Open-Pit Coal Mine have all entered a late phase of stable development. Their annual production of coal resources has essentially reached its peak and remains steady, with no significant changes in their mining scale. As mining activities progressively intensified to a certain level and then stabilized, the disruption to the ecosystem's structure and function accumulated over time. Consequently, the original ecosystem transitioned into a damaged state. Both the state and mining enterprises place a high priority on the preservation and rehabilitation of the ecological environment. They implement measures to restore ecosystems within mined areas, allowing the previously damaged ecosystems to gradually transition towards a new state of balance. The Inner Mongolia Yuanbaoshan open-pit coal mine and the Inner Mongolia Jungar Wusu open-pit coal mine have both entered the phase of early stable development. The annual production of coal resources has consistently risen, and the scale of mining operations has steadily expanded. As mining activities continue to escalate, the disruption to the ecosystem structure and function accumulates, ultimately transforming the once pristine ecosystem into a damaged one.

Impact of the five open-pit coal mines on ecosystem

The most immediate ecological and environmental impacts of open-pit coal mining are ground subsidence, land occupation, and the alteration of topographic and geomorphic landscapes. During the mining process of the open-pit coal mines, the mining pits damage the topography and geomorphology landscapes, the aquifer structures and the surface vegetation; the drainage of groundwater reduces the groundwater level around the pits; the industrial sites in the open-pit mining areas and the external spoil grounds occupy land and damage

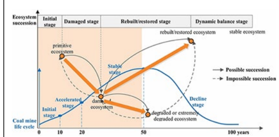
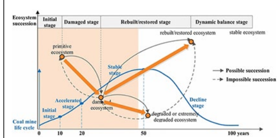
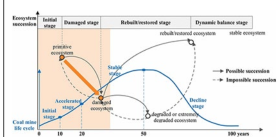
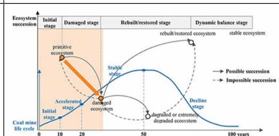
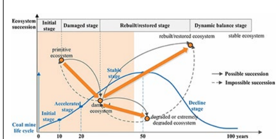
Name of coal mining area	History of mine construction	Life cycle stage	Ecosystem succession process	Graphical representation
Inner Mongolia Huolinhe open-pit coal mine	Construction began in September 1981 and production began at the end of August 1984	In the late stable development stage, the annual production of coal resources basically reached the highest and remained stable. The change from a damaged ecosystem to one that is degraded or severely degraded	The original ecosystem is enhanced to a certain extent by external interference and remains stable, and the damage to the structure and function of the ecosystem continues to accumulate, and the ecosystem becomes a damaged ecosystem. Mining enterprises attach importance to ecological restoration, and take reconstruction/restoration measures to the mined areas, and the damaged ecosystem gradually changes to another balanced state	
Inner Mongolia Yimin open-pit coal mine	Construction of the coal mine began in 1976, and it was put into production in 1985	In the late stable development stage, the annual production of coal resources basically reached the highest and remained stable. The change from a damaged ecosystem to one that is degraded or severely degraded	The original ecosystem is enhanced to a certain extent by external interference and remains stable, and the damage to the structure and function of the ecosystem continues to accumulate, and the ecosystem becomes a damaged ecosystem. Mining enterprises attach importance to ecological restoration, and take reconstruction/restoration measures to the mined areas, and the damaged ecosystem gradually changes to another balanced state	
Inner Mongolia Yuanbaoshan open-pit coal mine	Construction began in October 1990, trial production began in August 1998, and production was officially handed over in April 2005	In the early stable development stage, the annual production of coal resources continued to increase. The ecosystem is in a damaged state	The original ecosystem is enhanced by external interference, and the damage to the structure and function of the ecosystem continues to accumulate, and the ecosystem becomes the damaged ecosystem	
Inner Mongolia Jungar Wusu open-pit coal mine	Construction began in May 2006, and it was officially put into production in 2008	In the early stable development stage, the annual production of coal resources continued to increase. The ecosystem is in a damaged state	The original ecosystem is enhanced by external interference, and the damage to the structure and function of the ecosystem continues to accumulate, and the ecosystem becomes the damaged ecosystem	
Shanxi Pingshuo Antaibao open-pit coal mine	Construction began in 1982, and it was officially put into production in September 1987	In the late stable development stage, the annual production of coal resources basically reached the highest and remained stable. The change from a damaged ecosystem to one that is degraded or severely degraded	The original ecosystem is enhanced to a certain extent by external interference and remains stable, and the damage to the structure and function of the ecosystem continues to accumulate, and the ecosystem becomes a damaged ecosystem. Mining enterprises attach importance to ecological restoration, and take reconstruction/restoration measures to the mined areas, and the damaged ecosystem gradually changes to another balanced state	

Table 2. The life cycle stage and characteristics of the five major open-pit coal mines in China.

the surface vegetation[40–43]. In 2019, 36,105.00 km^2 of mined land was destroyed in China, accounting for about 0.37% of the country's land area[43]. The determination of coal mining-induced damaged land area primarily involves monitoring and delineating the impact boundaries of coal mining areas. Existing studies typically employ Deep Convolutional Neural Networks (DCNNs) to analyze multi-source remote sensing data and radar data for deriving such spatial information[44,45]. Firstly, the study employs 2022 Google Earth imagery with a 0.5-m spatial resolution to accurately delineate the boundaries of the five open-pit coal mines. Secondly, the scope of influence for coal mining is established based on the regional context at the initial development stage,

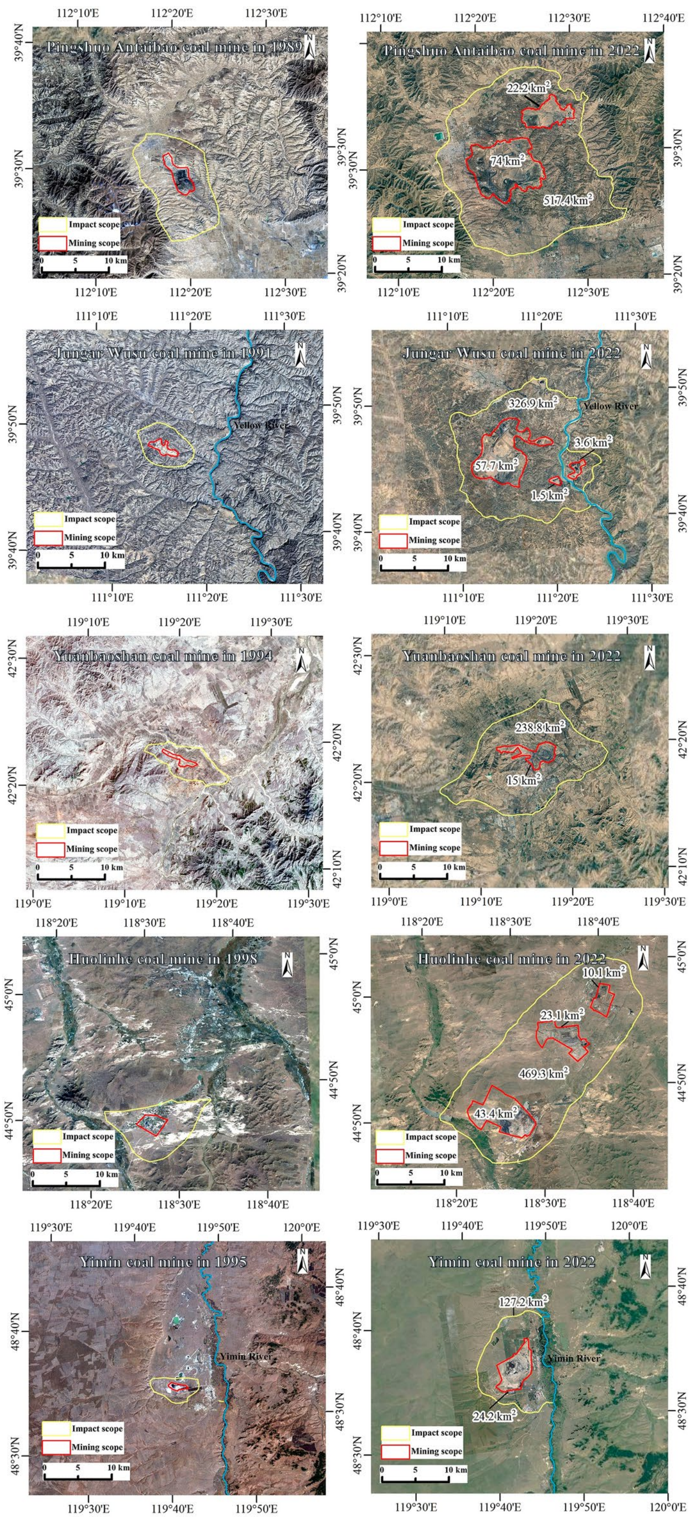


Fig. 7. Influence scope of coal mining activities of the five open pit coal mines in 2022.

including topographical and geomorphological characteristics, river networks, and the distribution of coal-related industries (Fig. 7). Among them, the background information of the initial development stage of coal mining comes from Landsat-5 satellite image data. In order to distinguish ground objects more easily, all images are taken in October.

The basis for determining the impact range of large open-pit coal mining: (1) Inner Mongolia Huolinhe open-pit coal mine: based on the images of the coal mine in 1998 and 2022, the influence scope of mining activities has expanded from the southwest to the northeast. These activities have had a significant impact on the surface features in the southern region of the mining area. (2) Inner Mongolia Yimin open-pit coal mine: based on the images of the coal mine in 1995 and 2022, the impact radius of mining operations has widened, spreading outward from its core, and the location of coal-related industries has solidified in the eastern and southern areas adjacent to the mine. (3) Inner Mongolia Yuanbaoshan open-pit coal mine: based on the images of the coal mine in 1994 and 2022, the influence scope of mining activities extends from the center outward in all directions, with its boundaries delineated according to the terrain features of the coal mine and the distribution of coal-related industries in the southern, eastern, and northern areas surrounding the mine. (4) Inner Mongolia Jungar Wusu open-pit coal mine: based on the images of the coal mine in 1991 and 2022, the influence of mining activities has expanded eastward, with their impact zones being delineated according to the distribution of the Yellow River and the terrain of the coal mines. (5) Shanxi Pingshuo Antaibao open-pit coal mine: based on the images of the coal mine in 1989 and 2022, mining activities exert a specific impact on the landmark features in the southern and northwestern regions of the mining area. The extent of this influence is delineated by the enclosed terrain characteristics of the mining site, which is nestled amidst mountains to the east, west, and north.

In 2022, the surface features affected by the mining activities of Inner Mongolia Huolinhe open-pit coal mine, Inner Mongolia Yimin open-pit coal mine, Inner Mongolia Yuanbaoshan open-pit coal mine, Inner Mongolia Jungar Wusu open-pit coal mine and Shanxi Pingshuo Antaibao open-pit coal mine (inside the yellow line in Fig. 7) were 469.30, 127.20, 238.80, 326.90 and 517.40 km^2, respectively, with a total area of 1679.60 km^2, which accounts for about 0.02% of China's land area. Among them, the mining areas of the excavated land (inside the red line in Fig. 7) were 76.60, 24.20, 15.00, 62.80 and 96.20 km^2, respectively, and the total mining area is 274.80 km^2. The Shanxi Pingshuo Antaibao open-pit coal mine has the largest area of excavated land among such mines in China, covering approximately one hundred thousand of China's land area. In 2022, the total coal production from open-pit coal mines in China reached 1.06 billion tons, with the combined production of the five such mines amounting to 142 million tons. According to the coal production, the total area of surface features affected by the mining activities of open-pit coal mines in China is estimated to be about 12,502.37 km^2, accounting for about 0.13% of China's land area. Open-pit coal mining activities result in the degradation of landform landscapes and extensive land excavation, leading to a significant waste of land resources as well as severe disruption of the ecosystem's structure and functions.

Measurement model of ecosystem resilience under the influence of coal mining

Measurement of ecosystem resilience in coal mining area

The measurement of ecosystem resilience involves the process of modeling and quantifying the resilience of ecosystems. Ecosystem resilience refers to the capability of an ecosystem to absorb or withstand disturbances and other stressors, reflecting its ability to recover to a stable state following a disturbance, and highlighting the inherent stability of the ecosystem itself[14,46]. There exists a threshold to the resilience of ecosystems, beyond which recovery to their initial state becomes exceedingly challenging. Suppose that there is an ecological index in any kind of ecosystem, which is inherent in the ecosystem under certain conditions, as long as the structure and factors of the ecosystem are stable, the index remains relatively stable. When external forces disrupt the ecosystem, both its structure and functions undergo changes. As external forces continue to exert their influence, the ecosystem undergoes four stages of development: encryption, resilience, yield and mutation. The encryption stage refers to the minimal impact of external disturbances on the ecosystem, where the structure and function of the ecosystem remain largely unaffected. The resilience stage denotes the phase in which the ecosystem exhibits stable resilience within a specific range of external disturbances, with the resulting damage being reversible. The yield stage refers to the phase at which the threshold of external disturbances is surpassed, leading to irreversible harm to the ecosystem. In this stage, the damages incurred are beyond the ecosystem's capacity to self-recover, necessitating human intervention for restoration efforts. The mutation stage refers to a phase in which an ecosystem undergoes a dramatic transformation due to the cumulative effects of external disturbances, environmental shifts, or internal interactions, significantly altering its structure and functions. At this stage, the ecosystem is seriously degraded, and the structure and function of the ecosystem need to be reconstructed manually.

Construction measurement model of ecosystem resilience in coal mining area

Ecosystem resilience encompasses both the strength of resilience and its limits. The resilience strength of an ecosystem refers to the inherent capacity of the ecosystem to withstand disturbances, which is determined by the state of the ecosystem itself. The resilience limit, on the other hand, denotes the range within which the ecosystem's resilience can vary, contingent upon the type of land cover and its diversity. The mining of coal resources damages the landscape, destroys vegetation and changes the original topography, thus destroying the structure and function of the ecosystem. Based on the strength and limits of ecological resilience, this research comprehensively takes into account factors such as landscape diversity, vegetation cover, land type, climate, and others, constructing a measurement model for assessing the resilience of ecosystems in coal mining areas. Among them, parameters such as landscape diversity, vegetation coverage, and land types can be obtained by interpreting remote sensing images through pre-processing, spatial analysis and other functions in ArcGIS 10.2.

Measurement model of the ecosystem resilience

(1) Calculating the landscape diversity indexes. Landscape diversity encompasses the variety and variability among distinct landscapes, encompassing their spatial configurations, functional processes, and temporal changes. The higher the index, the more diverse the landscape types, and the greater the ecological resilience[47]. The calculation formula is as follows:

$$H=-\sum_{i=1}^{n} P_i log_2\left(P_i\right) \tag{1}$$

where, H represents landscape diversity index; P_i represents the proportion of Class i ecosystem types, the ecosystem types are divided according to the actual situation of the study area, and the common types of ecosystems are forest ecosystem, grassland ecosystem, farmland ecosystem, urban ecosystem, etc.; n represents the number of ecosystem types in the coal mining area.

(2) Calculating vegetation indexes. The Normalized Difference Vegetation Index (NDVI) reflects the health and vitality of terrestrial vegetation by quantifying its growth rate and condition. The formula is as follows:

$$NDVI=\frac{NIR-\text{Red}}{NIR+\text{Red}} \tag{2}$$

where, *NIR* represents near infrared band; Red represents the red band of visible light, corresponding to MODIS bands 2 and 1, respectively. *NDVI* values range from − 1 to 1, with a value below 0 indicating no vegetation cover in the area.

(3) Calculating ecosystem resilience. A measurement model of ecosystem resilience is established based on the strength and resilience limit of the ecosystem[48]. The calculation formula is as follows:

$$E=\sigma\times\mu\times ECO_{res} \tag{3}$$

$$\sigma=\frac{H\times NDVI}{C_1\times C_2} \tag{4}$$

$$ECO_{res}=H\sum_{i=1}^{n} P_i\times S_i \tag{5}$$

where, E represents ecosystem resilience; σ represents the acceptable load coefficient (generally 0.08)[49]; μ represents the strength coefficient of ecosystem resilience; ECO_{res} represents the ecosystem resilience limit; C_1 represents the annual precipitation change rate in coal mining area; C_2 represents the annual temperature change rate in coal mining area; P_i represents the percentage of area covered by land type i in the coal mining area; S_i represents the resilience score of land type i in coal mining area, and the determination of resilience score is based on relevant research[48,50–52].

Recognition model of the ecological threshold

With the development and utilization of coal resources, the coal mine ecosystem will go through four stages: encryption, resilience, yield and mutation, and it requires breaking through the ecological threshold in order to transition successfully from the current stage to the next. Under the continuous disturbance of external forces, the ecological threshold that the structure and function of an ecosystem cross from never being significantly reduced (the encryption stage) to having reversible damage and maintaining stable resilience (the resilience stage) is called the elastic point; the ecological threshold that the ecosystem crosses from having reversible damage and maintaining stable resilience (the resilience stage) to having irreversible damage, being difficult to recover, and requiring artificial restoration intervention (the yield stage) is called the yield point; the ecological threshold that the ecosystem crosses from having irreversible damage, being difficult to recover, and requiring artificial restoration intervention (the yield stage) to being severely degraded and requiring artificial reconstruction of the ecosystem's structure and function (the mutation stage) is called the mutation point. To construct a model for identifying ecological thresholds, the Ecosystem Comprehensive Integrity Index (ECI) has been introduced. The size of the index is closely associated with the structural integrity, functional efficiency, and resilience of the ecosystem.

(1) Ecosystem structural integrity. The structural integrity of ecosystems is significantly characterized by the heterogeneity and connectivity present within the landscape. Landscape heterogeneity is quantified by Shannon evenness Index (*SHEI*) and mean patch fractal dimension (*MPFD*), while Landscape connectivity is quantified by the *CONTAG* and *CONNECT*. The ecosystem structural integrity *SC* is calculated by assigning corresponding weights to the four indexes.
(2) Ecosystem functional integrity. Ecosystem functional integrity mainly includes material balance, energy balance, water balance, etc. Net primary productivity (*NPP*) is selected to characterize the material and

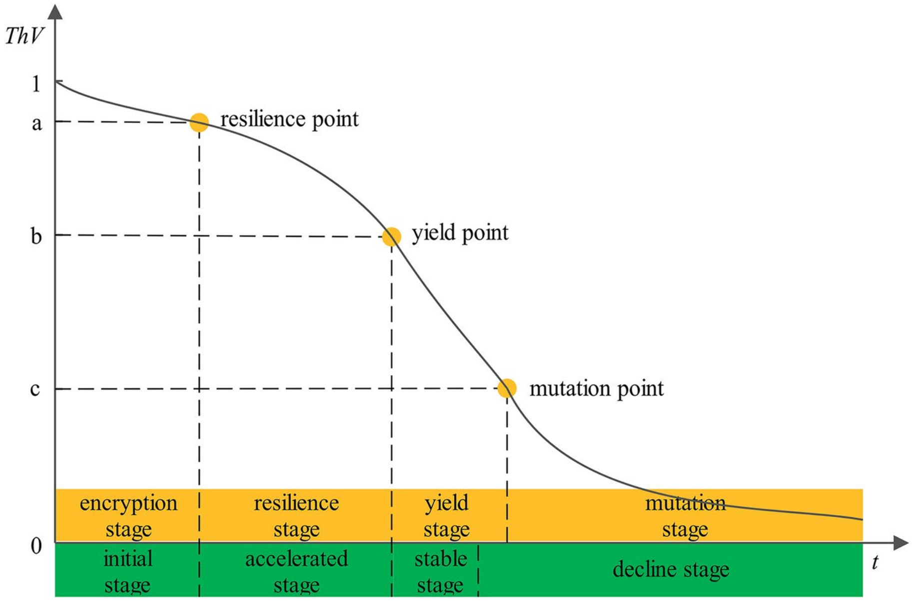


Fig.8. Ecological thresholds of different life cycle stages in coal mining area.

energy balance in the system, and based on the water balance equation, ecosystem water conservation is adopted as the water balance. The calculation formula is as follows:

$$Q = P - ET - R \tag{6}$$

where, *Q* represents water conservation (mm); *P* represents rainfall (mm); *ET* represents surface evapotranspiration (mm); *R* represents surface runoff (mm).

The ecosystem functional integrity *FC* is calculated by weighting net primary productivity (*NPP*) and water conservation (*Q*) accordingly.

(3) The measurement of ecosystem resilience is referred to above.
(4) The comprehensive ecosystem integrity index. In order to eliminate dimensional effects, the structural integrity, functional integrity and ecosystem elasticity of the ecosystem are normalized and given corresponding weights[53]. The calculation formula is as follows:

$$ECI = w_{sc} \times SC + w_{fc} \times FC + w_e \times E \tag{7}$$

where, *ECI* represents the comprehensive ecosystem integrity index; w_{sc}, w_{fc} and w_e respectively represent the weight of the corresponding item, and the weight assignment takes into account relevant research results.

(5) Change rate of the comprehensive ecosystem integrity index. The calculation formula is as follows:

$$ThV = \frac{ECI_j}{ECI} \tag{8}$$

where, *ThV* represents the change rate of the comprehensive ecosystem integrity index; ECI_j represents the comprehensive ecosystem integrity index in coal mining area at time point *j*.

In a coal mining area, there should be a corresponding constant (or constant interval) at each of the three ecological thresholds—the resilience point, the yield point, and the mutation point. This constant is closely related to the scale of mining operations, the technology employed, and the service life of the coal mining area. Verification of this relationship requires analysis through multiple case studies of coal mines. Assuming that the rates of change in the comprehensive ecosystem integrity index corresponding to the resilience point, yield point, and mutation point are denoted as a, b, and c respectively, one can deduce the temporal points of these three ecological thresholds by reverse calculation based on *ThV* (as shown in Fig. 8), considering the life cycle stage of the coal mining area. The negative impact of coal mining activities on the ecosystem is cumulative and lagging. The negative impact of mining disturbance on the ecosystem during the stable development of coal mining areas will only become prominent after a period of time. Therefore, the mutation point will appear after the stable development stage.

Discussion
To realize green, low-carbon, and sustainable development in coal mining areas, it is crucial and foundational to clearly understand the impacts of coal mining resources on the terrestrial ecosystem from a holistic and systemic perspective. After years of research and development, ideas such as ecological succession, landscape ecology, composite systems, and dynamic planning have been integrated into the field of mine reclamation and ecological restoration. As a result, they have significantly optimized the planning, design, and engineering practices of land reclamation and ecological restoration within mining areas. To some extent, it contributes to the achievement of ecological sustainability goals in mining areas. However, there remains a gap in our theoretical understanding of the essential inherent capabilities that contribute to systemic sustainability. Research on introducing circular waste management to mitigate the negative environmental impacts of mineral resource extraction also provides theoretical and practical support for achieving green and low-carbon development in mining areas[54,55]. However, there is still a gap in our theoretical understanding regarding the fundamental capacities that underpin systemic sustainability. Defining and quantifying ecosystem resilience offers a novel theoretical perspective for comprehending and remediating ecological issues within mining areas, as it serves as a crucial indicator of sustainability. The research elucidates the state maintenance and succession processes of a mining ecosystem in the face of disturbances, examining these phenomena from the perspective of the system's inherent resilience. This approach aims to deepen our understanding of the evolving nature of mining ecosystems and to devise more targeted restoration strategies.

Conclusions
In the process of promoting social and economic development, coal exploitation inevitably leads to a series of ecological issues. From a holistic and systemic perspective, the research delineates four stages in the life cycle of coal mining areas: the initial development stage, the accelerated development stage, the stable development stage and the decline development stage. The types of ecological succession in coal mining areas can be categorized as follows: terrestrial succession leading to a new terrestrial ecosystem, terrestrial to aquatic ecosystem transitions, or the development of an amphibious symbiotic ecosystem. Based on the characteristics of the coal mine life cycle stages and their corresponding ecological succession directions, we define the life cycle stages and ecosystem succession processes of China's five open-pit coal mines. The Inner Mongolia Huolinhe open-pit coal mine, the Inner Mongolia Yimin open-pit coal mine, and the Shanxi Pingshuo Antaibao open-pit coal mine have all entered a late stable development stage. The original ecosystems have been succeeded by damaged ecosystems, which are gradually transitioning into degraded or severely degraded states. The Inner Mongolia Yuanbaoshan open-pit coal mine and the Inner Mongolia Jungar Wusu open-pit coal mine have both transitioned into the early stable development stages. Consequently, the original ecosystems in these areas have been transformed into damaged ecosystems. Based on remote sensing data and coal production, the research quantitatively assessed the impact of surface coal mining on terrestrial ecosystems. In 2022, the total area of the earth's surface affected by open-pit coal mining activities in the country was approximately 12,502.37 km^2, accounting for about 0.13% of China's terrestrial land area. Of this, the area of the earth's surface affected by mining activities in the five major open-pit coal mines was about 1679.60 km^2, accounting for approximate 0.02% of China's terrestrial land area.

In the coal mining process, the ecosystem of coal mining area will go through four stages successively: encryption, resilience, yield and mutation, and it needs to break through the ecological threshold to cross the previous stage to the next stage. The resilience of ecosystems in coal mining areas is closely associated with landscape diversity, vegetation cover, land types, and climatic factors. A measurement model for ecosystem resilience in coal mining areas has been established, considering both the resilience strength and resilience limits. At the three ecological thresholds of ecosystem resilience, yield and mutation, the comprehensive ecosystem integrity changes significantly. The comprehensive ecosystem integrity index is introduced to build a conceptual model of ecological threshold recognition in coal mining area. The model ought to incorporate a corresponding constant, or a constant interval, at each of the three ecological thresholds. These constants are inextricably linked to the scale of mining operations, the technology employed, and the service life of the coal mining area. Their validity requires verification through multiple case studies of coal mines.

Data availability
All data generated or analyzed during this study are included in this published article.

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Declarations

Competing interests
The authors declare no competing interests.

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