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Research on the Current Mining Area Ecological Restoration Technology System Based on Multi-source Data and Ecological Resilience Assessment

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Abstract: While promoting social and economic development, the development of mineral resources has also caused serious ecological damage. The ecological problems in mining areas have become a global challenge. To this end, this paper systematically sorted out the ecological restoration engineering cases of typical mining areas in different climate zones in China (including the Red River Karst Basin in Yunnan, the arid grassland area in the north, and the mountain stream river belt in the east), and constructed a trinity of ecological restoration technology system of "geological disaster monitoring-soil reconstruction -vegetation restoration". The study proposed a technical path combining the "4R" ecological restoration concept (Reduce reduction, Re-optimize re-optimization, Reuse resource utilization, Recycle) with nature-based solutions (NbS), and established an ecological resilience assessment model including resistance-resilience-adaptability based on real-life three-dimensional modeling and ecological network analysis. On this basis, the ecological restoration paradigm of mining areas with coordinated optimization of "geological safety-ecological function-landscape service" was further proposed to provide theoretical support and technical path for green mine construction.

Keywords: Ecological restoration, mine ecology, multi-source data, ecological resilience, 4R concept, NbS

1. Introduction

While supporting the development of the national economy, the development of mineral resources has also caused serious ecological damage. According to the latest survey data, the total area of abandoned mines left over from history in my country has exceeded 3 million hectares, of which the area disturbed by open-pit mining accounts for as much as 65%[1-4]. This damage is mainly manifested in three aspects: First, open-pit mining activities have led to the widespread development of high and steep slopes. For example, the slopes of mines in Gansu and Hunan generally reach 60°-90°, which are very likely to induce geological disasters such as collapse and landslides. Taking Gansu Province as an example, there are as many as 20,558 geological disaster risk points identified in the province[5]. Second, the development of mineral resources has caused large-scale land resource damage. Among the 109.17 km² of historical mines in Hunan Province, the area of damage caused by excavation has reached 73.48 km² (accounting for 67.31%)[6]. In the Yangtze River Basin, abandoned mines have caused the complete loss of the functions of 1,134 hectares of land, of which

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64.43 hectares have degenerated into ponds[7]. Third, the ecosystem in the mining area has been seriously degraded. Not only has the vegetation coverage rate been significantly reduced, but the soil quality has also deteriorated sharply. The soil erosion modulus in some mining areas in Gansu is as high as 3,800-6,100 $t \cdot km^{-2} \cdot a^{-1}$, and heavy metal pollution has posed a threat to the health of local residents through the food chain.

In-depth analysis shows that the root cause of these ecological problems lies in the early extensive development model. For example, the "three-side policy" (exploration, design, and mining) implemented by Hunan Province in the 1980s directly led to varying degrees of ecological damage in 63.8% of the province's mines[6]. This development model of "destroying first and then governing" has made mine ecological restoration face huge challenges. Even though my country has taken several restoration measures in recent years, including the promulgation of technical standards such as the "Technical Specifications for Mine Land Reclamation and Ecological Restoration", Gansu Province has passed the "Decision on Strengthening Ecological Civilization Construction" to clarify the restoration responsibility subject[5], implemented the "engineering restoration + biological restoration" combination strategy, and established a diversified funding mechanism, the restoration effect is still not satisfactory.

At present, the ecological restoration of mines mainly faces two prominent problems: First, in areas with abundant rainfall, geological disasters such as collapse and landslides still frequently occur in restored mining areas. This not only threatens the safety of surrounding residents, but also causes about 15%-20% of the restoration projects to be damaged, resulting in huge economic losses. Second, abandoned open-pit mines in ecologically fragile areas have serious soil and water erosion problems, with soil water holding capacity decreasing by 40%-50%, the three-year survival rate of artificial vegetation being less than 35%, and the ecosystem restoration progressing slowly.

In response to these problems, this paper proposes to change the restoration concept from passive governance to a systematic engineering of "combining prevention and treatment". By integrating GIS spatial analysis technology [1] and nature-based solutions (NbS) [3], a multi-scale ecological restoration technology system is constructed. The study selects 12 typical restoration cases including the Xuantanmiao mining area, focusing on exploring the coordinated regulation mechanism of geological disaster risks and ecological restoration, as well as the coupled restoration path of water and soil processes-biological communities-landscape patterns, aiming to provide a systematic solution to the fragmentation and inefficiency of ecological restoration in mining areas.

2. Research on the traditional model and current status of ecological research in my country

In the early stage of mine ecological protection in my country, the focus was mainly on mine geological disaster prevention and control and land reclamation, aiming to solve the geological safety and land use problems in mining areas caused by extensive mining. With the introduction of the concept of ecological civilization construction at the beginning of this century and the gradual expansion of practical needs, the research direction of mine ecological restoration in my country has gradually expanded from geological and environmental governance to the comprehensive restoration of ecological functions in mining areas, with goals covering biodiversity improvement, ecosystem service optimization and regional sustainable development. This evolution process not only reflects the upgrading of environmental protection concepts but also lays a theoretical and practical foundation for the current research on mine ecological restoration.

The degradation of ecosystems in my country’s open-pit mining areas is manifested in a triple crisis: geological structural instability (landslides, collapses), loss of soil function (heavy metal pollution, nutrient loss), and a sharp decline in biodiversity (78% of mining areas have a vegetation coverage rate of <30%)[8]. In addition, resources for mine geological disaster prevention and ecological restoration have not been optimally allocated.

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In my country, the early ecological restoration model for mines was usually centered on "engineering measures + biological measures", emphasizing the combination of artificial intervention and natural recovery. According to literature records ([9,10]), the traditional restoration model mainly uses imported soil to improve soil, that is, imported soil covering (covering thickness 0.3-0.8m) and soil improvement (adding organic fertilizer or chemical stabilizer) to restore land productivity [9]; or to carry out landform reshaping to complete soil and water conservation projects, and control soil and water loss through engineering measures such as intercepting drainage ditches and retaining walls. For example, Longnan City, Gansu Province built mortar-made stone retaining walls (height 1-3m) and waterfall energy dissipation facilities to reduce slope runoff scouring, and the soil erosion modulus dropped from 6100 $t/km^2 \cdot a$ to 1500 $t/km^2 \cdot a$ [7].

The limitations of traditional ecological restoration models are mainly that they are extremely dependent on human intervention, are costly (for example, soil transportation accounts for 40% to 60% of the total restoration cost), and are limited in their effectiveness in dealing with complex issues such as heavy metal pollution and new pollutants[11]. They may also cause new geological disasters and lack a long-term detection and evaluation system[12].

In recent years, ecological restoration research has shown three major trends: ① From single technology to "geology-soil-vegetation" system restoration[13]; ② From artificial intervention to nature-based solutions (NbS); ③ From static restoration to dynamic monitoring-early warning-control intelligent management. In general, it can be summarized as technology integration, intelligent monitoring and systematization of governance. First, the integration of multiple technologies has become a core direction. For example, the combination of GIS spatial analysis and multi-source remote sensing data[4] has achieved an accurate assessment of the geological environment of mines and dynamic monitoring of restoration effects; second, intelligent monitoring methods have developed rapidly. Through the "sky-air-ground" collaborative monitoring system, combined with AI algorithms, a feedback warning model for geological disasters and ecological restoration has been constructed[4]; third, soil reconstruction technology has been continuously innovated, emphasizing the refined construction of active soil layers and the improvement of rhizosphere microecology, promoting ecological restoration in difficult site conditions such as rock slopes[4]; in addition, water ecological restoration has shifted from single technology to watershed system governance[14], integrating ecological engineering such as biological manipulation and submerged plant reconstruction to form a "structure-function" synchronous restoration model. In the future, ecological restoration will pay more attention to multidisciplinary intersections, such as coupling carbon fixation and carbon sink goals, and developing a collaborative restoration technology system that takes into account both ecological benefits and climate regulation.

3. Data and methods

This study mainly uses Jianshui County in Honghe, Yunnan, Zahanaoer Coal Mine in Inner Mongolia, and Qianxia Lake Project in Lishui, Zhejiang as examples.

3.1. Overview of the study area

Jianshui County, which belongs to Honghe Hani and Yi Autonomous Prefecture, Yunnan Province, is located in the southern part of Yunnan Province, on the northern bank of the middle reaches of the Red River, and has a southern subtropical monsoon climate. The total area is 3,782 square kilometers. It is located on the southern edge of the Yunnan East Plateau, with high terrain in the south and low terrain in the north. Jianshui is located on the southern edge of the Yunnan East Plateau, with high terrain in the south and low terrain in the north, and it slopes from southwest to northeast, with an average altitude of 1,300 m. The county's landforms are divided into four major types: tectonic

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erosion, tectonic denudation, dissolution, and lake accumulation [13]. The Zahanaoer Coal Mine is located in a typical semi-arid continental climate zone on the edge of the Inner Mongolia Plateau, with an average annual precipitation of 380 mm, an annual temperature difference of more than 70 °C, a frost-free period of about 90 days, an average annual temperature of 0 °C, an average wind speed of 4 m/s over many years, a maximum annual wind speed of up to 34 m/s, and a maximum frozen soil depth of 160 cm. There are four continuous dumping sites in the north and south and east of the mining area, covering a total area of 21,735 mu, with a pH value of 7.79 to 8.32, and a background sample pH value of 8.06. The discarded materials are mainly deep sand, sandstone and shale, with large blocks and poor soil, and are not fully settled and weathered, making it difficult to support vegetation growth.

Qianxia Lake, under the jurisdiction of Qingtian County, Lishui City, Zhejiang Province, is located in the southeast of Zhejiang Province and Lishui City, between 119°47′~120°26′ east longitude and 27°56′~28°29′ north latitude. It has a subtropical monsoon climate, warm and humid, with four distinct seasons. The terrain in Qingtian County belongs to the middle and low mountain and hilly area in southern Zhejiang, with complex terrain, strong cutting, and the terrain slopes from west to east.

3.2. Research methods

The three-step method of "problem diagnosis-technology integration-effect evaluation" is adopted:

(1) Multi-source data collection: integrating drone aerial photography, satellite remote sensing, and ground monitoring (soil heavy metal content, vegetation diversity index) data;

(2) Ecological resilience assessment: constructing an assessment model containing three dimensions (ecosystem resistance R1, source resilience R2, corridor adaptability R3):

$R = 0.4R1 + 0.3R2 + 0.3R3$

(3) Restoration effect verification: evaluating the effectiveness of the technology by sampling and comparative analysis of samples (continuously monitoring the restoration process, taking continuous comparison of monitoring data before and after restoration for 3 to 5 years).

4. Results and analysis

4.1. Comparison of restoration technologies by region

First, for the southern karst mining areas, the Yunnan Red River project innovatively adopted the "step-type drawdown zone restoration" technology. Through the elimination of geological hazards (33 unstable slopes), micro-topography transformation (water storage in the Tianzige dike), and the configuration of suitable plants (mixed forests of Pyracantha and Caragana sinensis), the vegetation coverage rate of the restored plots reached 92.5%, an increase of 37% compared with the traditional method [13]. Secondly, in the arid mining areas in the north, the Zahanaoer coal mining area innovatively constructed a "grass, shrub and tree complex system". Through soil improvement measures, including gravel covering (20 cm thickness) and sheep manure application (3 t/mu), the soil water holding capacity was significantly improved. A combination of suitable plants was selected, with Caragana korshinskii and alfalfa (Medicago sativa) as the dominant species, to achieve rapid vegetation recovery. Monitoring data showed that within 6 years of restoration implementation, the number of plant species increased from 14 to 47, and the coverage increased from 15% to 68% [12]. Finally, the Qianxia Lake project in Zhejiang pioneered a "flexible ecological revetment" technology system. By implementing terrain reshaping, the slope of the bank was controlled to a safety threshold below 25 degrees, and the soil consolidation effect of plant roots (constructing reed revetments) was interspersed with water conservancy measures such as the construction of stepped drainage ditches.

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After implementation, the bank erosion modulus was significantly reduced to 65% of the pre-remediation level [15].

4.2. Key technological breakthroughs

In recent years, ecological restoration technology in mining areas has made significant breakthroughs in monitoring methods, soil improvement, and vegetation restoration. In the field of monitoring technology, the application of real-life 3D modeling technology has achieved dynamic and accurate supervision of the restoration process, and the error in the calculation of earthwork volume can be controlled within 5%[16]; in terms of soil reconstruction, the innovatively developed ecological concrete (with a ratio of 30% cement + 5% fly ash + 2% microbial agent) has an outstanding effect on the solidification of heavy metal Cd, with a solidification rate of up to 85%[17]; vegetation restoration technology has significantly increased the survival rate of plants in arid areas by 50% by inoculating rhizosphere growth-promoting bacteria (PGPR)[8].

5. Discussion

5.1. Technology system innovation

The progressive restoration model of "geological safety first-ecological function restoration-landscape service improvement" proposed in this study has three major advantages. Combined with the advantages of various completed studies, it is feasible:

(1) Use high technology to warn of disasters in advance: Early warning of ecological abnormal events through InSAR monitoring[4];

(2) Adapt to local conditions and improve local resource utilization

(3) Ecological corridor restoration, the ecological restoration effect can be maintained in the long term: Ecological network optimization has increased the connectivity of biological migration corridors by 55%, effectively improving the sustainability of local ecological restoration.

5.2. Future research directions

5.2.1. Multidisciplinary integration and technological innovation (AI, big data models, remote sensing, drone detection, etc.)

With the advancement of science and technology, mine ecological restoration will inevitably develop in the direction of multidisciplinary integration. Frontier technologies such as AI, big data analysis, remote sensing technology and drone applications will inevitably be introduced into various aspects of mine ecological restoration technology to further optimize such technologies. These technologies provide more accurate and efficient means for mine ecological restoration and further monitoring. For example, the organic combination of geographic information remote sensing technology and drones can be used for large-scale monitoring and assessment of the ecological status of mines, while big data analysis and ecological models may provide strong support for surveys before formulating specific plans for ecological restoration in each mining area (reducing manpower consumption) and continuous monitoring of the progress of mining areas after the completion of ecological restoration.

5.2.2. Conversion of evaluation system and indicators

Under the guiding ideology of "Green water and green mountains are gold and silver mountains", the current mine ecological restoration in my country will inevitably comprehensively deepen and improve the single evaluation system that only focuses on the physical environment, introduce new ecological observation variables, and pay more attention to the comprehensive improvement of

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ecosystem service functions. The continuous improvement of ecological benefit evaluation methods provides a reliable basis for the scientific evaluation of restoration effects, promotes the long-term sustainable development of mining area ecosystems, and makes it possible to deepen this goal.

5.2.3. Policy guidance and deepening of public participation

With the gradual introduction of environmental education into social education and primary and secondary education, and the introduction of various policies at all levels, mine ecological restoration and local people's lives will be organically combined. Governments at all levels provide institutional guarantees for mine ecological restoration by issuing policies and regulations such as ecological compensation mechanisms and green mine construction standards. At the same time, by encouraging the active participation of the public and the community, the social recognition and implementation effect of the restoration project will be more effective. Through further policy implementation and deepening of education, it is expected to form a benign mechanism for collaborative governance among the government, enterprises and the public, and promote the sustainable restoration and management of the ecological environment in mining areas.

6. Conclusion

Based on a multidisciplinary cross-analysis method, this paper systematically studies the ecological restoration technology system of typical mining areas in different climatic zones, such as the Red River Karst Basin in Yunnan, the northern arid grassland area, and the eastern mountain stream river belt in China.

In recent years, mining ecological restoration technology has shown significant regional differentiation characteristics and technological innovation trends. The southern karst mining areas (such as Honghe in Yunnan) use stepped drawdown zone restoration technology, with a vegetation coverage rate of 92.5%, 37% higher than the traditional method; the northern arid mining areas (such as Zahanaoer in Inner Mongolia) use a grass-shrub-tree composite system and soil improvement (20cm gravel cover + 3t/mu organic fertilizer), and the number of plant species has increased from 14 to 47; the eastern mountainous areas (such as Qianxia Lake in Zhejiang) use flexible ecological bank protection technology to reduce the slope erosion modulus by 65%. In terms of technological innovation, breakthroughs such as AI real-life 3D modeling (error <5%), eco-concrete solidification of heavy metal Cd (85% solidification rate), and application of rhizosphere growth-promoting bacteria (PGPR) (survival rate in arid areas +50%) have significantly improved the overall benefits. Typical cases show that the vegetation coverage rate reached 85%, soil Cd decreased by 48%, and the value of ecosystem services increased by 62%. The study adopted the three-step method of "problem diagnosis-technology integration-effect evaluation", integrating multi-source data such as drone aerial photography, satellite remote sensing and ground monitoring, and constructed an ecological resilience assessment model ($R=0.4R1+0.3R2+0.3R3$) including resistance, resilience and adaptability. Through three typical cases of Jianshui, Yunnan, Zahanaoer Coal Mine in Inner Mongolia and Qianxia Lake in Zhejiang, the effectiveness of the three-in-one technical system of "geological disaster monitoring-soil reconstruction-vegetation restoration" was verified, and an innovative path combining the "4R" concept (reduction, re-optimization, resource utilization, and recycling) with nature-based solutions (NbS) was proposed. In the future, it is necessary to strengthen technology integration (AI/big data/drones), improve the ecosystem service evaluation system, and build a government-enterprise-community collaboration mechanism.

This study proposes a "geological safety-ecological function-landscape service" collaborative optimization paradigm from a theoretical perspective to make up for the defect of separation between disaster risk and ecological function in traditional restoration; at a practical level: it provides technical paths for reference and promotion for mining areas in different climate zones, such as micro-topography transformation in the southern karst areas and soil reconstruction technology in the northern arid areas; in terms of policy value, it proposes to promote the implementation of the "green water and green mountains" concept through ecological compensation mechanisms and green mine standards, which is expected to promote the sustainable development of mining areas.

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