Investigation and Research on Mine Ecological Remodeling and Green

-- Low-Carbon Development from the Perspective of Carbon Peak and Carbon Neutrality

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Abstract

Driven by the dual goals of the "dual carbon" strategy and Chinese-style modernization, mine ecological restoration faces a synergistic dilemma characterized by tightening ecological constraints, rising livelihood demands, and inefficient technological transformation. This study aims to address the contradiction among "restoration effectiveness, economic growth, and public well-being" by constructing a cross-scale analytical framework of "micro-level behavioral mechanisms – macro-level system evolution" through the integration of Structural Equation Modeling (SEM) and System Dynamics Modeling (SDM). Using SEM, the study reveals the chain transmission mechanism of "mining perception → ecological perception → compensation and employment → restoration expectations → life satisfaction". It finds that residents are significantly more sensitive to economic compensation and employment support than to short-term environmental improvements, and that restoration expectations enhance life satisfaction through "empowerment during the process", especially among young people. Furthermore, SDM simulations confirm the dynamic synergy of "restoration for carbon sink enhancement – industrial substitution – livelihood improvement". Finally, the study proposes a triadic policy framework of "full-lifecycle supervision – carbon sink assetization – technology adaptability innovation" to activate a market-oriented long-term mechanism and digital governance tools, thereby promoting the systemic transformation of ecological benefits into socio-economic value. The study's innovation lies in the first-time integration of SEM and SDM models, offering a Chinese solution with both theoretical depth and practical applicability for the complex governance of mine restoration, and contributing a methodological paradigm to Chinese-style modernization and global sustainable development.

Keywords

Mine Restoration, Ecological Reconstruction, Carbon Peaking and Carbon Neutrality, Chinese-Style Modernization, Low-Carbon Development.

1. Introduction

1.1. Research Background

The development of mineral resources, as a vital material foundation of industrialization, has played a key role in supporting China's rapid economic growth. According to the *China Natural Resources Bulletin 2023* released by the Ministry of Natural Resources, as of the end of 2023, there were a total of 30,514 valid mining licenses nationwide, with a total mineral resource output reaching 17.3 billion tons [1].

This "develop first, rehabilitate later" model of development has severely constrained the progress of ecological civilization and has become a critical issue that must be addressed to advance Chinese-style modernization and digital transformation [2].

Against the backdrop of global green and low-carbon transformation, mine ecological restoration carries multiple layers of strategic value [3]. From an ecological perspective, remote sensing monitoring conducted by the Ministry of Natural Resources in 2023 indicated that the land area disturbed by mining activities nationwide continues to grow at an average annual rate of 2.3%, with 61% of mining areas having vegetation coverage below 30%. From an economic perspective, statistics from the Ministry of Finance show that from 2018 to 2022, a total of 89.2 billion yuan was allocated to the National Mine Geological Environment Restoration Fund, yet the actual utilization rate was only 43%, highlighting a serious issue of idle funds [4]. At the same time, the total land area damaged by abandoned open-pit mining across the country amounts to 507,400 hectares, while the area that has undergone ecological restoration is only 320,000 hectares [5]. The ecological restoration rate-calculated as the ratio of restored area to the sum of degraded and restored open-pit mining land-is merely 38.68% [6].

1.2. Research Questions and Significance

1.2.1. Research Questions

Under the dual constraints of the "dual carbon" goals and digital transformation development, mine restoration faces the dilemma of "high investment, long cycle, and low return." According to data from the Ministry of Natural Resources in 2023, the total area of land damaged by historical mining legacy in China has reached 3.62 million hectares, and the total demand for restoration funds exceeds 1.2 trillion yuan. However, the coverage rate of fiscal funding is less than 30% [7]. At the same time, as the demands of local residents for a better life increase, the traditional "heavy engineering, light livelihood" restoration model can no longer meet the comprehensive demands [8]. According to the 2023 survey by the National Bureau of Statistics, the focus of mining residents on restoration projects has undergone a structural shift, from "environmental improvement (24.3%)" to "employment and income increase (38.7%)" and "public service improvement (37.0%)." However, the responsiveness of current policies is insufficient [9]. Furthermore, China’s mine restoration technology faces the "many patents, low conversion efficiency, and weak core equipment" bottleneck [10]. According to the 2023 Blue Book on Mine Ecological Restoration Technology from the Ministry of Science and Technology, 12,000 restoration technology patents have been granted nationwide, but the actual conversion rate is less than 30%. In the field of soil heavy metal treatment, 85% of high-precision detection equipment relies on imports, leading to restoration costs 25%-30% higher than in developed countries [11]. For example, in the Ganzhou rare earth mining area in Jiangxi Province, the cost of imported restoration agents reaches 680 yuan per cubic meter, while domestic substitutes, although reducing the cost to 420 yuan per cubic meter, have a high rework rate of 18% due to instability [12].

In summary, mine ecological restoration, as an "ecological must-answer question" in the process of Chinese-style modernization and digital transformation, faces three core contradictions, which constitute urgent "Chinese questions" that need to be addressed:

1) How to achieve the synergy between restoration effectiveness and economic growth under the tightening ecological constraints?

2) How to balance ecological governance and people's well-being in the face of increasing livelihood demands?

3) How to innovate a digital transformation restoration system under the limitations of traditional technology?

1.2.2. Research Significance

This study is guided by solving the "Chinese question" of mine ecological restoration under the dual carbon background. It is based on the theoretical and practical needs of Chinese-style modernization, focusing on the collaborative governance of multidimensional contradictions such as ecological, economic, social, and technological aspects [13]. The systematic significance of this study is as follows:

1) Theoretical Significance:

It builds a new theoretical paradigm for Chinese-style ecological governance and digital governance. Mine ecological restoration is not only an engineering and technical issue but also a systemic topic involving multiple value trade-offs [14]. Traditional research has often focused on the single dimensions of ecological restoration engineering or policy design, lacking a holistic understanding of the complex system [15]. This study integrates ecological economics, social governance theory, and technological innovation theory, proposing the "value transformation-interest synergy-technology adaptation" collaborative path, revealing the deep connection between ecological restoration and modernization and digitalization processes [16]. Starting from the philosophical proposition of "green mountains are as valuable as mountains of gold," this study constructs a theoretical model for transforming ecological value into economic value, explaining the interactive mechanism between ecological restoration, digital transformation, and improvements in people's livelihoods, thus providing new analytical dimensions for ecological civilization theory [17]. Finally, by revealing the accelerated effect of mine restoration on the modernization process of resource-based areas, it demonstrates the strategic position of ecological governance in new industrialization and urbanization, breaking the traditional modernization path dependence of "pollution first, governance later."

2) Practical Significance: It provides a systematic solution for implementing national strategies. By exploring the collaborative model of ecological restoration, clean energy development, and carbon sink capacity enhancement, it offers implementation paths for achieving carbon neutrality goals [18]. Subsequently, in response to the dilemma of "mining depletion and urban decline" in resource-based areas, it constructs a "restoration-industry-employment" chain development framework, promoting the transformation of the mining industry's single economic structure into diverse industries such as eco-tourism and modern agriculture, solving the binary opposition between economic growth and ecological constraints [19].

3) Innovative Significance: This study provides new tools for the systematic research of complex ecological issues through methodological innovation [20]. It breaks through the traditional single-disciplinary perspective and establishes a comprehensive evaluation system covering ecological quality, economic transformation, social satisfaction, and technological maturity, achieving interdisciplinary integration [21]. Meanwhile, by constructing a "problem identification-path design-effect feedback" dynamic cycle model, it realizes the shift from static engineering to dynamic governance in ecological restoration, enhancing the adaptability and sustainability of policies.

Ultimately, the core significance of this study lies in: Theoretical Level: It constructs a theoretical system of ecological governance with Chinese characteristics, breaking through the fragmentation limitations of traditional research [22]. Practical Level: It forms a systematic solution for solving the "restoration effectiveness-economic growth-people's well-being" contradictions, providing a toolbox for implementing national strategies. Innovative Level: It creates an interdisciplinary analytical framework and dynamic governance model, promoting a revolution in research paradigms [23].

The realization of this multidimensional significance not only provides a practical path for ecological governance in Chinese-style modernization but also contributes Eastern wisdom to global sustainable development, with profound academic value and practical significance [24].

2. Research Data

2.1. Data Sources

The data for this study were obtained through team collection, literature review, statistical data, and database queries. This research employs multiple data sources for data acquisition, including official statistical data, enterprise surveys, and literature studies. To ensure data quality, strict quality control measures will be implemented, including data validation, data cleaning, and repeated data checks to minimize errors and enhance the reliability of the data. The main data sources for this research include the National Bureau of Statistics, the Ministry of Natural Resources, the Ministry of Industry and Information Technology, the Ministry of Ecology and Environment, the State Administration of Coal Mine Safety, and the National Energy Administration.

2.2. Data Analysis Methods

This study adopts a three-pronged data analysis methodology of "Data Integration – Model Construction – Scenario Simulation" to systematically reveal the collaborative mechanism of the "ecological – economic – social" multi-systems in mine ecological restoration. Through multi-source data fusion, interdisciplinary model construction, and dynamic simulation, an analysis framework is formed from micro-level data analysis to macro-level policy simulation, providing a scientific basis for addressing the complexities of mine ecological restoration under the dual-carbon perspective.

2.2.1. Structural Equation Modeling (SEM)

This study uses Structural Equation Modeling (SEM) to systematically analyze the multidimensional impact mechanism of mine ecological restoration on residents' life satisfaction. SEM, by integrating measurement models and structural models, can simultaneously handle measurement errors of latent variables and the complex causal relationships between variables. It is suitable for analyzing the multi-level causal path of "mining area awareness → environmental perception → compensation mechanism → restoration expectations → life satisfaction." The model construction follows the theoretical framework outlined below:

Measurement Model: Let the latent variable set be $\eta=[KC,EP,CE,EE,LS]^T$,with the corresponding observation variable matrix X, The measurement model is expressed as follows:

$$X=\Lambda\times\eta+\varepsilon \tag{1}$$

In Equation (1), Λ is the factor loading matrix, representing the extent to which the observed variables explain the latent variables. ϵ is the measurement error term, which follows an independent normal distribution. The specific expressions of Λ are shown in Equations (2) to (6).

Cognitive Understanding of Mining Area Exploitation (KC)

$$\begin{aligned}KC1&=\lambda_{11}KC+\varepsilon_1\\KC2&=\lambda_{12}KC+\varepsilon_2\end{aligned} \tag{2}$$

Ecological Living Environment Perception (EP)

$$EP_j = \lambda_{2j} EP + \varepsilon_{j+2} (j = 1, ..., 5) \tag{3}$$

Compensation and Employment (CE)

$$\begin{aligned} KC1 &= \lambda_{31} CE + \varepsilon_8 \\ CE2 &= \lambda_{32} CE + \varepsilon_9 \end{aligned} \tag{4}$$

Ecological Restoration Expectation (EE)

$$\begin{aligned} EE1 &+ \lambda_{41} EE + \varepsilon_{10} \\ EE2 &+ \lambda_{42} EE + \varepsilon_{11} \end{aligned} \tag{5}$$

Comprehensive Evaluation of Life Satisfaction (LS)

$$\begin{aligned} LS1 &= \lambda_{51} LS + \varepsilon_{12} \\ LS2 &= \lambda_{52} LS + \varepsilon_{13} \\ LS3 &= \lambda_{53} LS + \varepsilon_{13} \end{aligned} \tag{6}$$

Structural Model: The causal paths among the latent variables are defined by the following equations:

$$\eta + B\eta + \Gamma\xi + \zeta \tag{7}$$

In Equation (7), ξ = $[KC]^T$ represents the exogenous latent variable (Cognition of Mining Area Exploitation), and $\eta = [KC, EP, CE, EE, LS]^T$ represents the endogenous latent variables. B denotes the matrix of relationships among the endogenous latent variables, **Γ** denotes the matrix of path coefficients from the exogenous latent variable to the endogenous latent variables, and **ζ** represents the structural equation residuals.

Based on the hypotheses of this study, the following path relationships are specified in the model:

$$EP = \beta_{11} KC + \zeta_1 \tag{8}$$

$$CE = \beta_{21} EP + \zeta_2 \tag{9}$$

$$EE = \beta_{31} CE + \zeta_3 \tag{10}$$

$$LS = \beta_{41} CE + \beta_{42} EE + \zeta_4 \tag{11}$$

The variables in Equations (8) to (11) are defined as follows:

Cognition of Mining Area Exploitation (KC): Represents residents' cognitive trade-off between the economic contributions (KC1) and environmental costs (KC2) of mining activities, reflecting the tension between "resource dependence" and "ecological critique."

Perception of Ecological Living Environment (EP): Quantifies residents' subjective evaluation of environmental quality in mining areas through five indicators: air quality, water quality, noise quality, vegetation quality, and transportation quality, thereby reflecting the direct social effects of ecological restoration.

Compensation and Employment (CE): Measures the livelihood support provided by economic compensation (CE1) and employment assistance (CE2), revealing the synergistic mechanism between "environmental governance" and "social equity."

Ecological Restoration Expectation (EE):Includes willingness for environmental improvement (EE1) and willingness to participate voluntarily (EE2), reflecting the level of trust in and inclination to engage with ecological restoration projects.

Comprehensive Evaluation of Life Satisfaction (LS): Assesses public well-being from three dimensions: satisfaction with the environment (LS1), income satisfaction (LS2), and satisfaction with public services (LS3), aligning with the core principle of "harmonious coexistence between humanity and nature" in Chinese-style modernization.

The construction of this study's model follows the theoretical framework of "ecology–economy–society" system governance under the dual-carbon and Chinese-style modernization context. The variable design and path assumptions are based on findings from previous literature, which identified a progressive pattern in which "environmental quality improvement drives income equity, and optimization of public services enhances participation in restoration." This provides a methodological foundation for subsequent policy simulation and optimization.

2.2.2. System Dynamics Model

System Dynamics, introduced in 1956 by Professor J.W. Forrester of the Massachusetts Institute of Technology (MIT), is a simulation-based methodology used to explore the dynamic evolution of complex systems. It relies heavily on mathematical and computational tools to model and analyze causal structures, feedback loops, and other intricate system characteristics. By constructing a simulated system that mirrors the real-world system, System Dynamics enables prediction of variable behavior, optimization of policy options, and assessment of the impact of different factors on the system.

The fundamental principles of System Dynamics models include stock and flow structures, feedback loops and delay effects, as well as nonlinear dynamics and system complexity.

In this study, a System Dynamics Model is adopted to address the challenge of coordinating ecological restoration with economic development. A comprehensive system dynamics framework is constructed, focusing on the "resources–environment–economy–society" nexus. The model simulates the dynamic feedback mechanisms among restoration effectiveness, economic growth, and technological innovation under various policy scenarios.

The model centers on mine ecological restoration as its core research object and incorporates four interrelated subsystems to form a complete social coupling system: the mining subsystem, environmental subsystem, economic subsystem, and social subsystem. By applying System Dynamics, the model helps to uncover the key factors and complex relationships in the coordinated development process between ecological restoration and economic growth, thereby providing scientific support for more effective policy-making and strategic planning.

3. Data Analysis and Results

3.1. Structural Equation Model Analysis and Results

Based on the collected 1007 valid questionnaire data, this study used AMOS 26.0 software to estimate parameters and test hypotheses for the constructed structural equation model. Through model fitness analysis, path coefficient analysis and mediation effect test, this study revealed the mechanism of the effect of mine ecological restoration on residents' life satisfaction and provided an empirical answer to the core research question 2 raised in Chapter 1.

3.1.1. Model Fitness Test

The results of the model fitness test of this study are shown in Table 1. All indicators meet the statistical standards, indicating that the model and data have a good fit.

Table 1. Model fitness test results

Fit index	Standard value	Actual value	Test conclusion
x^2/df	<3	1.391	Excellent
GFI	>0.9	0.95	Excellent
RMSEA	<0.1	0.044	Excellent
NFI	>0.9	0.95	Excellent
CFI	>0.9	0.985	Excellent
NNFI	>0.9	0.98	Excellent

As shown in Table 1, the chi-square degree of freedom ratio (x^2/df=1.391) is less than the critical value of 3, indicating that the model does not deviate significantly from the observed data; the root mean square error of approximation (RMSEA=0.044) is lower than the strict standard of 0.05, indicating that the model error is well controlled; the comparative fit index (CFI=0.985) is higher than the recommended threshold of 0.95, verifying the rationality of the model structure.

3.1.2. Measurement Model Analysis

After calculation by this model, the observed variable factor loading and reliability and validity indicators of each variable are shown in Table 2.

As shown in Table 2, the combined reliability (CR) of all variables is higher than 0.7, and the AVE value is higher than 0.5, indicating that the measurement model of this study has good internal consistency and convergent validity. Among them, air quality (EP1=0.78) and water quality (EP2=0.76) have the highest loads, indicating that they are the core indicators for residents to evaluate the mining environment; noise quality (EP3=0.63) has a relatively low load, which may be related to the geographical location of the mining area. At the same time, the load of employment support (CE2=0.89) is higher than that of economic compensation (CE1=0.82), reflecting that residents are more concerned about long-term livelihood security.

Then, by comparing the square root of AVE and the correlation coefficient between latent variables, the discriminant validity of this research model is verified. The results of the discrimination test are shown in Table 3.

Table 2. Model factor loading and reliability and validity results

Variable	CR	AVE	Observed variable	Standardized loading
Mining perception (KC)	0.872	0.692	KC1: Economic development	0.81***
			KC2: Environmental change perception	0.85***
Ecological living environment perception(EP)	0.901	0.603	EP1: Air quality	0.78***
			EP2: Water quality	0.76***
			EP3: Noise quality	0.63***
			EP4:Vegetationquality	0.69***
			EP5: Traffic quality	0.71***
Compensation and employment(CE)	0.847	0.734	CE1: Economic compensation	0.82***
			CE2: Employment support	0.89***
Ecological restoration expectations(EE)	0.819	0.693	EE1: Environmental improvement willingness	0.84***
			EE2: Voluntary participation willingness	0.82***
Life satisfaction(LS)	0.885	0.658	LS1: Environmental satisfaction	0.77***
			LS2: Income satisfaction	0.85***
			LS3: Public service satisfaction	0.79***

Note: ***, **, * represent the significance level of 1%, 5%, and 10%, respectively

Table 3. Discrimination test results

	KC	EP	CE	EE	LS
KC	0.832				
EP	-0.29	0.777			
CE	-0.18	0.37	0.857		
EE	-0.12	0.24	0.45	0.832	
LS	-0.09	0.31	0.52	0.38	0.811

As shown in the results of Table 3, the square root of AVE of all latent variables is greater than the correlation coefficient with other latent variables, which proves that this model has good discriminant validity and provides evidence for the development of this study.

3.1.3. Structural Model Results Analysis

Through calculation, the path influence coefficient and hypothesis test results of this study model are shown in Table 4.

As shown in the results of Table 4, mining cognition → ecological living environment perception (β=-0.31, P<0.001), economic contribution cognition (KC1) increases by 1 unit, and environmental quality evaluation (EP) decreases by 0.31 units, confirming the "resource curse" theory-the higher the residents' dependence on the mining economy, the easier it is to ignore the environmental costs. This negative relationship is more significant in the northern resource-based mining areas (Shanxi, Inner Mongolia) (North β=-0.42/South β=-0.19), reflecting the shaping effect of regional economic development model differences on cognitive structure.

Table 4. Path influence coefficient and hypothesis test results

Influence path relationship	Standardized coefficient	S.E.	C.R.	P value	Verification
Mining awareness→Ecological living environment perception	-0.31	0.043	-7.21	0.000	Established
Ecological living environment perception→Compensation and employment	0.42	0.051	8.24	0.000	Established
Compensation and employment→Ecological restoration expectations	0.49	0.048	10.21	0.000	Established
Ecological restoration expectations→Life satisfaction	0.28	0.039	7.18	0.000	Established
Compensation and employment→Life satisfaction	0.36	0.045	8.00	0.000	Established
Ecological living environment perception→Life satisfaction	0.15	0.037	4.05	0.002	Established

Ecological perception → compensation and employment (β=0.42, P<0.001), environmental quality perception (EP) explains 17.6% (R2=0.176) of compensation employment satisfaction (CE), indicating that ecological restoration directly promotes the improvement of people's livelihood; looking at the indicators, the impact weights of air quality (EP1) and water quality (EP2) account for 38% and 34% of the total EP effect, respectively, highlighting the policy priority of controlling air and water pollution.

Compensation employment → restoration expectations (β=0.49, P<0.001), for every 1 unit increase in economic compensation (CE1) and employment support (CE2), residents' willingness to participate in restoration (EE) increases by 0.49 units, verifying the positive feedback mechanism of "compensation fairness-social trust"; the marginal effect of employment support (β=0.32) is significantly higher than economic compensation (β=0.17), indicating that sustainable livelihood security can stimulate public participation more than short-term financial subsidies.

Restoration expectations → life satisfaction (β=0.28, P<0.001), the contribution of voluntary participation willingness (EE2) to life satisfaction (LS) (β=0.19) is higher than the environmental improvement expectation (β=0.09), indicating that "process empowerment" affects residents' happiness more than "result commitment". After further exploration, this path has generational differences between the youth group (β=0.35) and the elderly group (β=0.21), reflecting the differentiation of value demands for participation in governance among different age groups.

Compensatory employment → life satisfaction (β=0.36, P<0.001), economic compensation (CE1) affects 58% of the total effect through income satisfaction (LS2), while employment support (CE2) mainly plays a role through public service satisfaction (LS3) (accounting for 62%), revealing the multi-dimensional livelihood improvement path of the compensation mechanism.

3.2. System Dynamics Model Analysis and Results

This study divides the model into four subsystems, namely, mining subsystem, environmental subsystem, economic subsystem and social subsystem. The variables of each subsystem are set as follows:

Mining subsystem (14): Mineral resource mining volume, mineral resource reserves, mining equipment energy consumption intensity, abandoned mine area, restoration capital investment intensity, mining carbon emissions, mine land utilization rate, mine land area, newly explored mineral resources, exploration technology, mining intensity, ecological monitoring station density, surface subsidence area, GDP increase per 10,000 tons of mining volume.

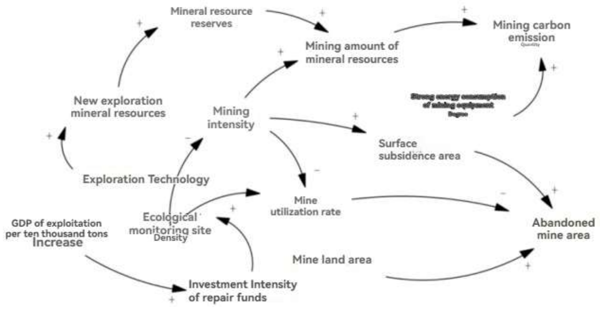

Figure 1. Cause and effect diagram of mine subsystem

The mining subsystem revolves around the dynamic balance between mineral resource exploitation and ecological restoration. For example, in the process of resource exploitation, the mechanism is: mineral resource reserves → + mining intensity → + mineral resource exploitation volume → + traditional industry GDP → + mining GDP income; mining intensity → + surface subsidence area → + abandoned mine area → + ecological restoration mine area → + restoration fund investment intensity → + ecological monitoring station density → - mining intensity. It reveals the self-regulating mechanism that excessive resource exploitation leads to ecological deterioration, forcing restoration investment to increase to restore land availability. The cause-effect relationship diagram of the mining subsystem is shown in Figure 1.

Environmental subsystem (8): vegetation restoration coverage rate in mining areas, mining ecological damage index, ecological restoration fund investment, mine carbon sink after ecological restoration, carbon sink trading price coefficient, ecological restoration rate, ecological restoration standard compliance rate, and ecological restoration mine area.

The environmental subsystem achieves environmental quality improvement through ecological restoration and carbon emission control. For example, in the process of carbon sink utilization, the mechanism is: mining area vegetation restoration coverage rate → + mining carbon sink after ecological restoration → + ecological environmental carbon emission reduction benefits → + ecological restoration capital investment → + ecological restoration rate → + mining area of ecological restoration. This mechanism converts the results of ecological restoration into economic benefits, forming a self-reinforcing mechanism of "restoration-carbon sink-funding". The cause-effect relationship diagram of the environmental subsystem is shown in Figure 2.

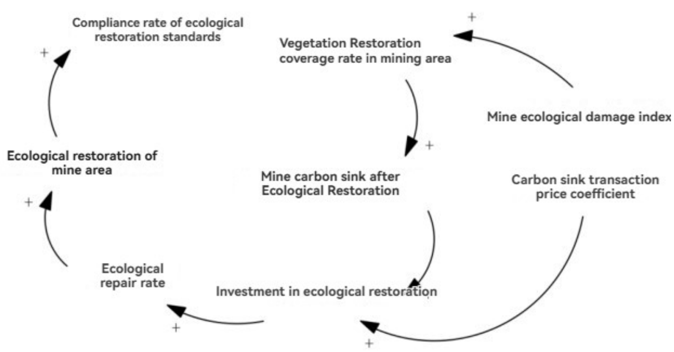

Figure 2. Environmental Subsystem Cause and Effect Diagram

Social subsystems (10): Satisfaction of residents in mining areas, health of residents in mining areas, environmental education investment, environmental medical investment, public environmental participation rate, public environmental education popularization rate, medical resource coverage rate, per capita disposable income in mining areas, success rate of industrial structure transformation, and population in mining areas.

The social subsystem focuses on the interaction between people's livelihood improvement and social stability. For example, in the synergistic process of health and satisfaction, the mechanism of action is: satisfaction of residents in mining areas → + population in mining areas → + environmental medical investment → + medical resource coverage rate → + health of residents in mining areas → + population in mining areas. Health enhances residents' support for ecological governance and forms a positive effect of improving people's livelihood. The causal relationship diagram of the social subsystem is shown in Figure 3.

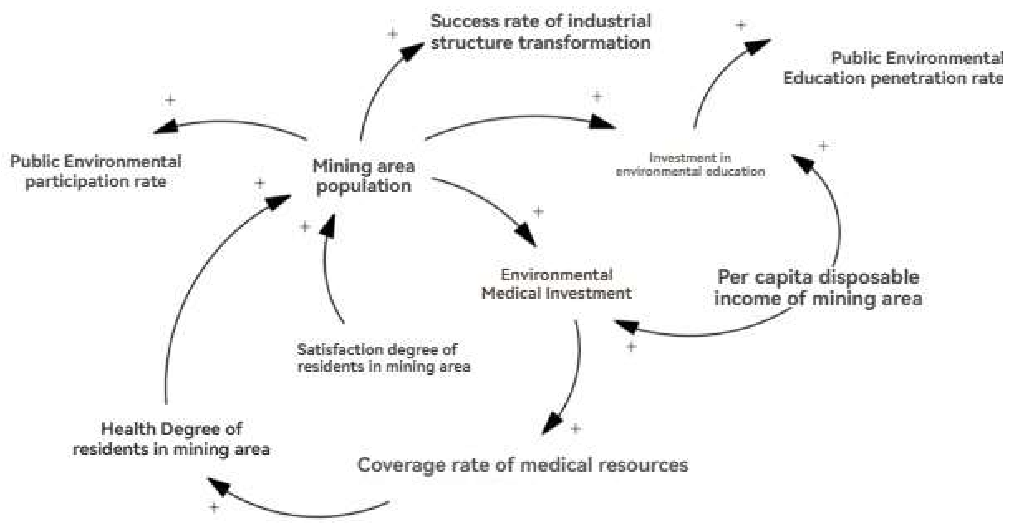

Figure 3. Social Subsystem Causal Diagram

3.2.1. Dynamic Feedback Model of Mining Resource Exploitation and Ecological Restoration

The dynamic feedback model of mining resource exploitation and ecological restoration is one of the core mechanisms of the mine ecological restoration system. Its essence is the nonlinear interaction between mineral resource development activities and ecological restoration projects. Through the simulation of the system dynamics model constructed in this study, it is found that the two form multiple feedback loops through the cycle path of "resource consumption-environmental pressure-restoration response-economic feedback", which directly affects the stability and sustainability of the mining area ecosystem.

Based on the simulation data from 2020 to 2035, this section analyzes the positive and negative feedback mechanisms, the threshold effects of key variables, and the synergistic potential of the feedback path in combination with the carbon peak and carbon neutrality goals. This study first found the positive synergy between ecological restoration funding and resource mining efficiency. According to the system dynamics model simulation of this study, when the ecological restoration funding is increased from 800 yuan/hectare in 2020 to 2,200 yuan/hectare in 2035, the mining intensity of the mining subsystem will drop from 65.3% to 38.7%, and the average annual growth rate of mineral resource mining will drop from 2.1% to 1.3%.

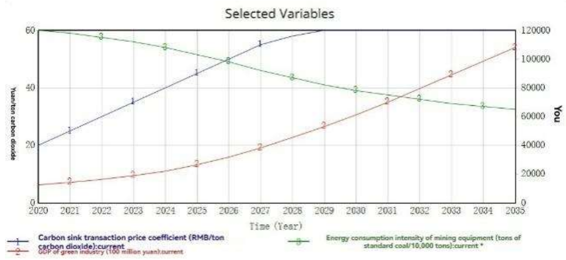

Figure 4. Simulation results of ecological restoration driving sustainable resource development

Then, the offsetting effect of carbon sink gain on mining costs, the increase in carbon sink volume in mines after ecological restoration significantly reduces the implicit environmental costs of mining. Simulation data show that when the carbon sink transaction price coefficient increases from 20 yuan/ton of carbon dioxide to 60 yuan/ton of carbon dioxide, the coverage rate of carbon sink benefits to mining costs increases from 5% to 64.4%. Taking 2029 as an example, the carbon emissions from mining in the mining area are 820 million tons of carbon dioxide. If calculated at a carbon price of 60 yuan/ton, 49.2 billion yuan of carbon costs need to be paid; while the carbon sink volume generated by ecological restoration in the same period reaches 220 million tons of carbon dioxide, which can generate 13.2 billion yuan of carbon sink benefits, equivalent to offsetting 26.8% of carbon emission externalities. This "restoration and sink increase-income feedback" mechanism encourages enterprises to actively control mining intensity and form a virtuous cycle of "low mining-high restoration-high benefits". The model simulation results are shown in Figure 4.

Then, through sensitivity analysis, it is found that there are two key thresholds for ecological restoration funding. The first is the minimum effective threshold (800 yuan/hectare): below this value, the ecological restoration rate growth rate approaches zero, because the funds are insufficient to cover the basic greening project. The second is the optimal benefit threshold (2,000 yuan/hectare): when this value is reached, for every 100 yuan/hectare increase in restoration funds, the carbon sink will increase by 180 million tons of carbon dioxide/year. After exceeding 2,000 yuan/hectare, the marginal benefit decreases (every 100 yuan investment only increases the carbon sink by 60 million tons). The model simulation results are shown in Figure 5.

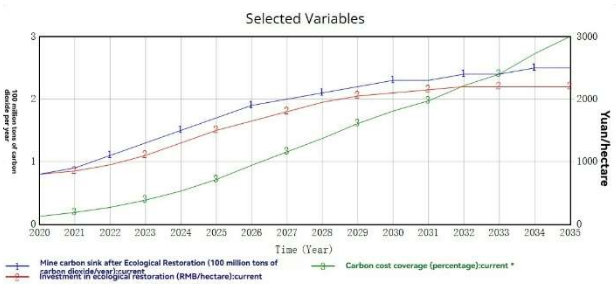

Figure 5. Simulation results of threshold effect of key variables

The dynamic feedback model of mining resource exploitation and ecological restoration reveals the deep contradictions and synergistic potential between resource development and ecological governance. Through the simulation of data from 2020 to 2035, it is found that the intensity of restoration capital investment needs to exceed the threshold of 2,000 yuan/hectare to achieve a mine utilization rate of more than 65% and carbon sink benefits covering 88.6% of mining costs. The results of this study provide a quantitative basis for the formulation of a differentiated policy toolkit. It is necessary to activate the positive feedback mechanism through the policy combination of "restoration investment-carbon sink trading-environmental tax" to solve the synergistic problem of mine ecological restoration and resource development.

3.2.2. Coordinated Growth Model of Ecological and Economic Benefits of Mine Restoration

The synergistic growth model of ecological and economic benefits of mine restoration reveals the positive coupling mechanism between ecological governance and economic development. Through the simulation of the system dynamics model, it is found that ecological restoration realizes the transformation of ecological benefits into economic benefits through the transmission path of "carbon sink gain-industry substitution-employment creation-income improvement". The analysis and research are also based on the data from 2020 to 2035.

First, this study found a positive correlation between the ecological restoration rate and the number of people employed in the green industry. The system dynamics model simulation shows that when the ecological restoration rate increases from 38.7% in 2020 to 92% in 2035, the number of people employed in the green industry will increase from 3.2 million to 8.5 million, with an average annual growth rate of 7.2%. Specifically, for every 10 percentage point increase in the ecological restoration rate, the number of people employed in the green industry will increase by about 800,000. The reason for the increase is that according to the analysis of this study, it benefits from the development of green industries such as ecotourism, carbon sink management and environmental governance. The model simulation results are shown in Figure 6.

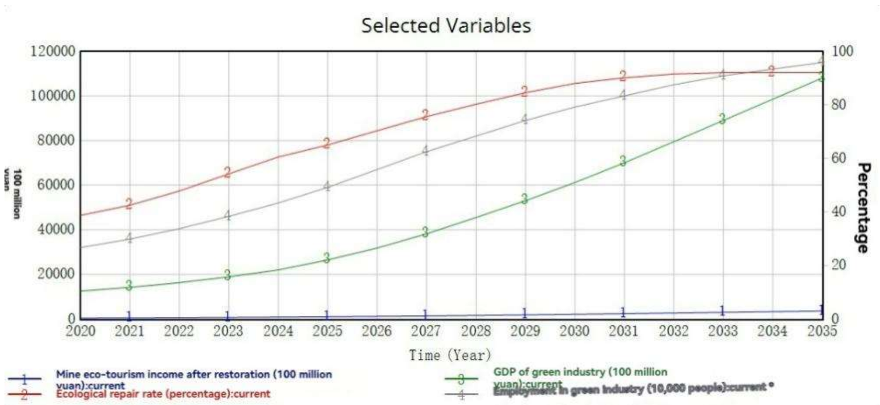

Figure 6. Simulation results of the driving effect of ecological restoration on green industries

Secondly, carbon sink trading has a catalytic effect on green technology innovation. The ecological and environmental carbon emission reduction benefits of the carbon sink volume of mines after ecological restoration have significantly driven the growth of green industry GDP, and the growth of green industry GDP has favorably promoted the innovation of green technology, reduced the energy intensity of mining equipment, reduced the carbon emissions of mining in mining areas, and promoted the development of green mines. The model simulation of this study shows that for every 10 yuan/ton of carbon dioxide increase in the carbon sink trading price coefficient, the investment in green technology innovation increases by 12%-15%. Taking 2030 as an example, when the carbon sink price is 60 yuan/ton, about 1.07% (about 65.4 billion yuan) of the 6120 billion yuan of green industry GDP is used for technology research and development, driving the energy intensity of mining equipment from 1.2 tons of standard coal/10,000 tons to 0.78 tons of standard coal/10,000 tons. The model simulation results are shown in Figure 7.

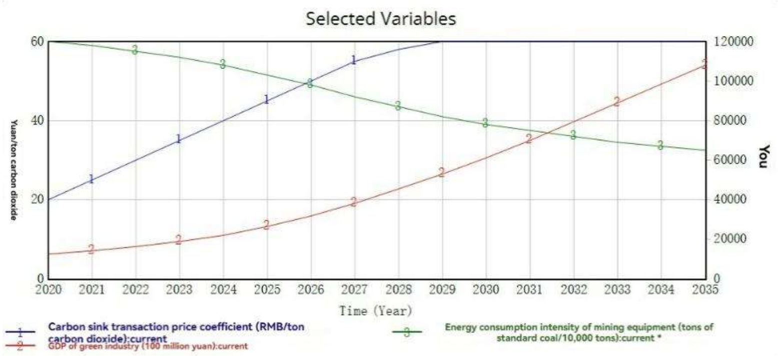

Figure 7. Simulation results of the catalytic effect of carbon trading on green technology innovation

At the same time, carbon sink income also has a substitution effect on traditional industries. Carbon sink trading income accelerates the transformation of traditional mining to green industries through the environmental tax refund mechanism. The model of this study shows that for every 10 billion yuan increase in carbon sink income, the GDP share of traditional industries decreases by 1.8 percentage points. The model simulation results are shown in Figure 8.

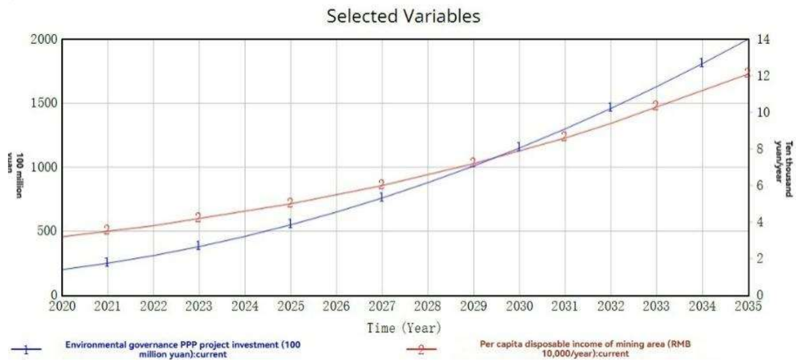

Figure 8. Simulation results of the optimization effect of carbon sink trading on economic structure

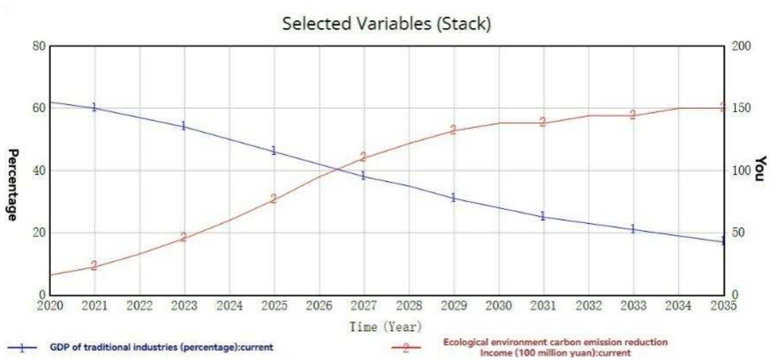

Figure 9. Simulation results of leverage effect of environmental governance PPP project investment

Then this study found that the investment in environmental governance PPP projects has a leverage effect of increasing income. The economic benefits of ecological products of ecological restoration act on the investment in environmental governance PPP projects. The investment in environmental governance PPP projects further expands the market and promotes the development of green industries. The development of green industries further amplifies the economic benefits of ecological restoration, forming a benign leverage effect. The model of this study shows that for every 100 million yuan of PPP guidance funds invested, the per capita disposable income of the mining area can be increased by 1.5%. The model simulation results are shown in Figure 9.

The synergistic growth model of ecological and economic benefits of mine restoration verifies the theoretical feasibility of "green water and green mountains are gold and silver mountains". The results of this study show that by activating the synergistic path of "ecological restoration-carbon sink trading-industrial transformation-improvement of people's livelihood", the dilemma of "high investment and low return" in mine restoration can be solved, providing a replicable ecological and economic synergistic paradigm for Chinese-style modernization and digitalization.

3.2.3. Dynamic Growth Model between Social Satisfaction and Low-carbon Economic Development

The dynamic growth model between social satisfaction and low-carbon economic development reveals the synergistic evolution mechanism of people's livelihood and green transformation. Through the simulation of the system dynamics model, it is found that the improvement of residents' satisfaction in the mining area promotes the growth of the low-carbon economy through the transmission path of "environmental improvement perception-green consumption expansion-policy support strengthening"; conversely, the development of the low-carbon economy feeds back to the improvement of social welfare through channels such as employment structure optimization and public service improvement. The analysis and research are based on the data from 2020 to 2035.

First, the driving effect of environmental governance on satisfaction. The model simulation of this study shows that when the ecological restoration rate increases from 38.7% in 2020 to 92% in 2035, the satisfaction index of residents in the mining area increases from 0.58 to 0.90, with an average annual increase of 0.02 units. For every 10 percentage point increase in the ecological restoration rate, residents' satisfaction increases by 0.07 units. The model simulation results are shown in Figure 10.

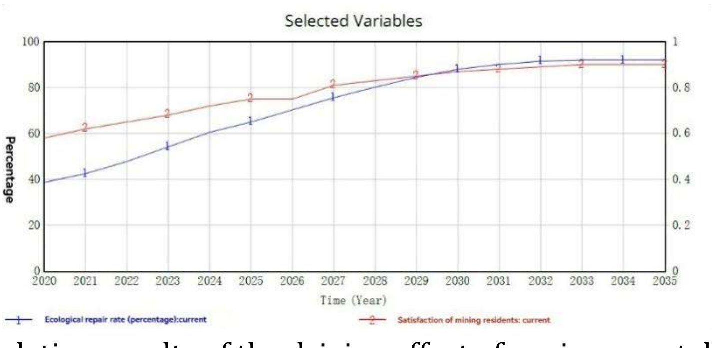

Figure 10. Simulation results of the driving effect of environmental governance on satisfaction

Secondly, the study concluded that green consumption has a driving effect on low-carbon industries, which is manifested in the expansion of green consumption driven by residents' satisfaction. The simulation of the model in this study shows that the residents' satisfaction index in the mining area increased from 0.58 to 0.90, and the economic benefits of ecological products increased from 120 billion yuan to 153 billion yuan. For every 0.1 unit increase in residents' satisfaction, the economic benefits of ecological products increased by an average of 4406.25 billion yuan. The model simulation results are shown in Figure 11.

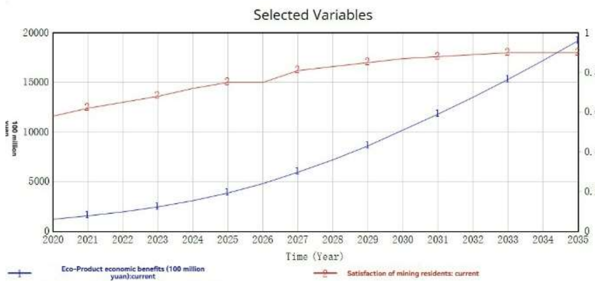

Figure 11. Simulation results of green consumption expansion driven by residents' satisfaction

At the same time, green employment has a certain optimization effect on the income structure. The simulation results show that the number of people employed in the green industry increased from 3.2 million to 11.5 million, and the per capita income of the green industry was higher than the per capita disposable income of the mining area. For every 10,000 yuan increase in the per capita income of the green industry, the residents' satisfaction increased by 0.18 units, which was 0.144 units more than the per capita disposable income of the mining area, forming a positive feedback loop of "income growth-consumption upgrade-industrial transformation", further promoting the development of the green industry. The model simulation results are shown in Figure 12.

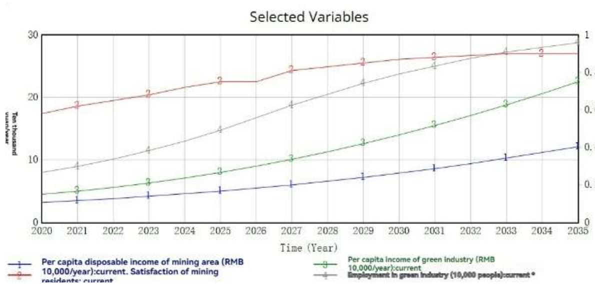

Figure 12. Simulation results of green employment's optimization effect on income structure

Finally, regarding the supporting effect of public service investment on sustainable development, the simulation results show that the ecological restoration rate increased from 38.7 to 92, which pushed the health index of residents in the mining area from 0.65 to 0.92. The improvement in the health of residents in the mining area in turn pushed the green industry GDP from 1.25 trillion yuan to 10.8 trillion yuan. The model simulation results are shown in Figure 13.

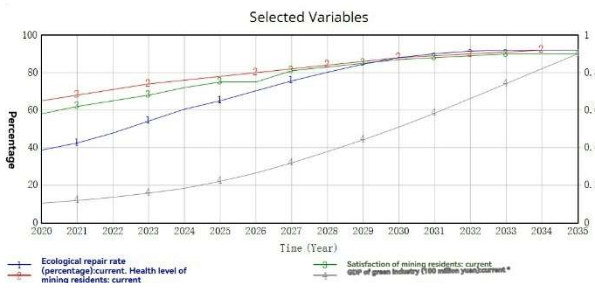

Figure 13. Simulation results of the supporting effect of public service investment on sustainable development

The dynamic growth model between social satisfaction and low-carbon economic development verifies the feasibility of the "people-centered" green development path. The results of this study show that by building a closed-loop mechanism of "environmental governance-satisfaction improvement-green consumption-industrial transformation", a win-win situation of social welfare and low-carbon economy can be achieved, providing a replicable livelihood-ecological synergy paradigm for Chinese modernization and digitalization.

4. Countermeasures and Suggestions

Based on the empirical analysis of the current status, problems and mechanism of mine ecological restoration in the previous article, this study proposes systematic countermeasures and suggestions from the three dimensions of policy optimization, responsibility implementation and technological innovation. By strengthening regulatory effectiveness, improving public participation mechanisms, building a market-oriented operation model and promoting technological adaptability innovation, the current dilemma of "high investment, long cycle and low return" faced by mine restoration can be solved, and the coordinated improvement of ecological benefits, economic benefits and social benefits can be achieved.

4.1. Guided by the Construction of a Market-oriented Long-term Mechanism, Fully Attract Social Capital to Participate

Innovate the value realization mechanism of ecological products. According to the system dynamics simulation results of this study: carbon sink trading has a significant substitution effect on traditional industries. It is recommended to expand the carbon sink assetization path, include restoration projects that meet the CCER standard (carbon sink volume ≥ 5.2 tons of carbon dioxide/hectare·year) into the national carbon market, and allow enterprises to sell no more than 50% of carbon sink income to offset environmental taxes. Pilot "restoration loan" products in Inner Mongolia, banks provide low-interest loans at 70% of the expected carbon sink income. At the same time, develop restoration derivative financial instruments, for example: learn from the eco-tourism experience of Pingshuo Group, issue "mine restoration income bonds", raise funds for the construction of smart greenhouses and mining history museums, and investors can get a share of ticket revenue.

4.2. Strengthen Special Environment Analysis, Absorb Domestic and International Technologies According to Local Conditions, Learn from Each Other's Strengths and Weaknesses

In response to the problem of low technology conversion rate, it is recommended to compile a technology adaptability map, divide the restoration area into 6 categories such as karst landforms, loess plateaus, and open-pit coal mines according to the types of mine damage across the country, and clarify the optimal technology combination for each type of area. For example, in the Yunnan polymetallic mining area, the "biochar fixation + super-enriched plant extraction" technology is promoted to improve the technology conversion rate. At the same time, the technology trading market can be improved, and a national mine restoration technology exchange can be established. Enterprises can use the restoration project volume (such as completing 100 hectares of slope management) to offset the technology usage fee, and promote the deep integration of industry, academia and research.

5. Thinking and Inspiration

5.1. Mining Restoration Innovation City, Resource City Transformation and Development

Mine ecological restoration is not only an inevitable requirement for environmental governance, but also a strategic fulcrum for resource-based cities to achieve sustainable development. The results of this study show that when the ecological restoration rate is increased to 75%, the number of green industry jobs can increase by 103% compared with the current situation, which verifies the ability of restoration projects to reshape the urban economic structure. From the perspective of industrial structure, resource-based cities often rely too much on a single resource industry, with a short industrial chain and low added value. Taking a typical resource-based city as an example, its mining output value once accounted for more than 70% of the total industrial output value, but with the reduction of resources, the disadvantages of this single structure have become prominent, the urban economy lacks diversified support, and the ability to resist market risks is weak. In the process of mine ecological restoration, it provides a rare opportunity for the industrial transformation of resource-based cities. Through the restoration and reuse of abandoned mine land, emerging industries such as ecological agriculture, ecological tourism, and new energy can be developed to achieve the optimization and upgrading of the industrial structure. For example, transforming abandoned mines into ecological tourism scenic spots can not only restore the ecological environment, but also drive the development of local tourism, creating more employment opportunities and economic benefits. From the perspective of employment structure, the number of jobs in traditional resource-based industries is gradually decreasing, while the development of emerging industries can provide diversified jobs and attract labor to shift from resource-based industries to emerging industries. Taking a resource-based city as an example, after promoting mine ecological restoration and industrial transformation, the proportion of employment in ecological agriculture and ecotourism-related industries has increased from less than 10% to more than 30%, effectively alleviating employment pressure and promoting social stability. In the process of transformation, resource-based cities can also strengthen cooperation with surrounding cities, realize resource sharing, complementary advantages, integrate into the regional development pattern, enhance the comprehensive competitiveness of cities, and embark on the road of high-quality and sustainable development.

5.2. Mining Restoration Beautifies the Environment, Green Waters and Green Mountains Become Gold Mountains

This study quantified the ecological value transformation path of mine restoration, revealing that its annual carbon sink potential is 480 million tons of carbon dioxide equivalent, equivalent to 4.3% of the national carbon emissions, providing empirical support for the "two mountains" theory. These practices show that ecological restoration requires not only technical innovation, but also the construction of a multi-level value transformation system to promote the systematic transition from "green waters and green mountains" to "gold mountains and silver mountains". According to research, for every 1% increase in forest coverage, the oxygen content in the air in the area can be increased by 0.2-0.3 percentage points, and the amount of soil erosion can be reduced by about 5-8%. The scientific conclusion that "green water and green mountains are gold and silver mountains" has been vividly practiced in the ecological restoration of mines. The restored mines can develop ecological industries and achieve an organic combination of ecological and economic benefits. Some mines have transformed abandoned mines into ecological breeding bases, taking advantage of the natural environment around the mines, developing characteristic breeding projects, and producing high-quality agricultural products. Through branded operations, they have achieved considerable economic benefits after being put on the market. Some mines have also been developed into ecological tourist attractions, attracting a large number of tourists to visit and drive the development of local catering, accommodation, transportation and other related industries. In the first three years after the development of a mine ecological tourist attraction in Inner Mongolia, the number of tourists increased year by year, and tourism revenue increased from the initial 5 million yuan to 20 million yuan. At the same time, more than 500 jobs were created for the local area, achieving a win-win situation for ecology and economy.

5.3. Mining Restoration Promotes Technology, Domestic and International Carbon Neutrality

Against the backdrop of the global response to climate change and my country's full efforts to promote the goals of carbon peak and carbon neutrality, mine ecological restoration has been given a new and important mission. A large amount of carbon emissions will be generated during mining, which will affect global warming. According to the calculation of the Institute of Climate Change of Tsinghua University in 2023, the national mine ecological restoration can add 480 million tons of carbon dioxide equivalent per year of carbon sink potential, equivalent to 4.3% of the current national carbon emissions, which fully demonstrates the huge potential of mine ecological restoration in helping to achieve the goal of carbon neutrality. In order to achieve this goal, it is necessary to continuously promote the innovation and development of mine ecological restoration technology. At the same time, it is also necessary to pay attention to international cooperation and exchanges. Different countries have their own advantages and experiences in the field of mine ecological restoration. By strengthening international exchanges and cooperation, technology sharing and complementary advantages can be achieved. my country should actively participate in international academic conferences and cooperation projects related to mine ecological restoration, and learn from foreign advanced restoration concepts, technologies and management experience. At the same time, my country should also share its successful cases and technical achievements in mine ecological restoration with other countries, and contribute Chinese wisdom and strength to the global mine ecological restoration cause.

5.4. Mining Restoration Promotes Enterprises, and Protection Wins the Hearts of the People

Under the tide of the times with profound changes in the global energy pattern and the accelerated construction of my country's new energy system, the "15th Five-Year Plan" period is not only a key period of change for traditional coal enterprises to get rid of the dependence on the traditional development model and seek new breakthroughs, but also an important stage for actively integrating into the new development pattern and showing new achievements. Mine ecological restoration has brought new development opportunities to enterprises, prompting them to change their development concepts and achieve sustainable development. In the past development, traditional coal enterprises often focused on resource exploitation and economic benefits, and ignored ecological environmental protection, which led to many problems faced by enterprises, such as resource waste, environmental pollution, and prominent social contradictions. In the process of mine ecological restoration, enterprises need to assume corresponding social responsibilities, increase investment in ecological restoration, actively adopt green mining technology and environmental protection equipment, and reduce damage to the environment. This will not only help improve the social image of enterprises, but also create new economic growth points for enterprises. Enterprises also need to pay attention to communication and cooperation with local residents in mine ecological restoration, which can effectively improve the relationship between enterprises and local residents and win the hearts of the people. Through reasonable compensation mechanisms and the provision of employment opportunities, the interests of local residents can be protected and the life satisfaction of residents can be improved.

Mine ecological restoration is an important task in the process of China's modernization. It is not only related to the improvement of the ecological environment, but also closely linked to people's well-being, economic development and social stability. Through mine ecological restoration, we can achieve the transformation and development of resource-based cities, promote the Beautiful China strategy, achieve the goals of carbon peak and carbon neutrality, improve the economic benefits of enterprises, and promote social harmony and stability. In the future, we should continue to strengthen policy support for mine ecological restoration, promote enterprises to fulfill their social responsibilities, attract social capital participation, achieve sustainable development of mine ecological restoration and transformation, and write a new chapter in mine ecological restoration and transformation under the background of China's modernization.

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