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A Framework for Post-Mining Area Restoration Based on Social-Ecological System Analysis

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Abstract: Mining activities have had lasting negative impacts on the ecological and socio-economic environments of resource-dependent areas. Although numerous practices and studies have focused on sustainable mining and mine restoration, few have examined how social factors influence ecological recovery. Addressing the interdisciplinary and cross-system challenges brought by post-mining impacts requires a deeper understanding of human-environment interactions. This study aims to explore sustainable restoration and reconstruction pathways for social and ecological systems in post-mining areas. Grounded in social-ecological systems (SES) theory, the research employs a literature review, case studies, and network analysis. We first define post-mining SES concepts, establish SES prototypes and an analytical framework, characterize system features, and conceptualize dynamic trajectories. Based on these findings, adaptive management strategies are proposed for post-mining areas. The results indicate that identifying systemic pressures and vulnerabilities, while aligning SES multi-level dynamics, is essential for restoration. Cross-scale governance involving multiple stakeholders can enhance SES network resilience.

Keywords: social-ecological system; post-mining area restoration; sustainability; ecological recovery; resilience; vulnerability

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1. Introduction

As the human population and socio-economic activities expand, the demand for energy and materials has steadily increased. Mining, as a major human activity involving geological resources, has profoundly altered the natural environment. While mining has brought benefits to resource-dependent areas by supplying raw materials, boosting the economy, creating jobs, improving livelihoods, and fostering infrastructure and community development [1,2], the originally isolated ecosystems in these regions have evolved into tightly coupled social-ecological systems. At the same time, mining operations have caused widespread disruption to landscapes and ecosystems, reducing their natural capacity for recovery [3-5]. Despite the adoption of sustainable mining policies emphasizing environmental responsibility, inadequate enforcement and ongoing mining activities, along with abandoned mines, continue to cause lasting damage to water, soil, air, landforms, geology, vegetation, and biodiversity [5,6]. These ecological damages further intensify pressures on social and economic systems, resulting in geological hazards, land degradation, contamination of food and water, mass migration, and deteriorating public health [1,2,7].

Over the past 50 years, post-mining land reclamation and ecological restoration have been globally researched topics, with the primary goal of restoring post-mining landscapes to a self-sustaining state capable of supporting productive use and delivering social benefits. This extensive and fragmented body of knowledge has been systematically reviewed [2,8,9]. With advancements in landscape ecology and restoration ecology, research on post-mining landscape restoration increasingly emphasizes systemic and interdisciplinary approaches. However, actual restoration actions often focus on localized, micro-scale engineering projects, reducing complex systems to specific problems related to water, soil, and vegetation [5,10]. Although there has been a growing body of research on ecosystem services in post-mining areas over the past five years, issues such as the scale and equitable distribution of these services remain unaddressed. Most resilience trajectory studies have focused on species abundance changes over time, using similarity indicators based on species structure and composition [9]. However, social benefits are not considered in these metrics, and the long-term resilience of both social and ecological systems in response to known or unknown disturbances remains unclear.

Many large mining sites are expected to close within the next decade [9]. The restoration of post-mining landscapes involves complex ecosystem functions and diverse social factors, with various restoration elements interacting across spatial and temporal scales. The development of post-mining areas is not only driven by economic and social relationships but also depends on the sustainability of the ecosystem, forming feedback loops that influence environmental benefits and human well-being. Therefore, it is challenging to achieve restoration goals with a single approach. It is crucial to consider the social-ecological systems of mining areas and focus on sustainable development throughout the post-mining restoration process. Based on the introduction, this research is guided by the following research questions:

(1) Define social-ecological systems (SES) within post-mining areas, review SES analytical frameworks, and describe the SES of post-mining regions.

(2) Summarize disturbances and threats within the ecological and social dimensions of post-mining areas, evaluate vulnerability factors affecting SES, clarify system dynamics, and explore ways to enhance system resilience.

(3) Analyze the relationship between vulnerability and resilience drivers within SES and develop an action model for restoring and reconstructing post-mining areas.

2. Conceptual Definition

2.1. Concept of SES in the Post-Mining Area and Characteristics

The concept of social-ecological systems (SES) is continually evolving, with various interpretations and terms used to describe its meaning [11]. SESs are based on the theory of complex adaptive systems (CAS), encompassing key resources involved in interactions between human society and ecological systems. Ecological and social components interact across multiple levels and scales, with humans responding to systemic changes through institutional mechanisms. This multidimensional feedback between humans and the environment shapes diverse types of SESs [12,13]. Within defined spatial and temporal contexts, SESs can be categorized according to different levels and scales [14].

Resilience and vulnerability are core characteristics essential for analyzing how SESs respond to disturbances and changes, as they are interrelated and complementary [15]. Resilience is generally defined as a system's ability to absorb impacts while maintaining its core functions and structure, as well as its capacity for self-organization, learning, and adaptation [16]. Vulnerability refers to the system's weak points, including its exposure, sensitivity, and adaptive capacity to disturbances or changes [15,17]. Understanding both resilience and vulnerability is crucial for effectively managing the risks and changes faced by SESs [14,18].

Mine closure and restoration are iterative and dynamic processes [19]. This paper adopts the concept of an "adaptive cycle" to model lifecycle management of mining areas, including phases such as operation, closure, abandonment, restoration, and reconstruction, which parallel stages of disturbance, damage, restoration, and learning. Vulnerability is primarily defined as the state or attributes of the system after landscape damage and before recovery, while resilience is linked to actions taken during and after restoration aimed at reducing vulnerability and enhancing resilience to address post-mining impacts and future disturbances.

2.2. SES Analysis Framework for Post-Mining Landscapes

A framework integrates concepts, methods, and tools to explain social-ecological systems (SES), requiring a multidisciplinary analytical approach [13,20]. Various SES analysis frameworks have been developed to structure complex adaptive systems based on diverse problems and requirements [21]. Post-mining areas form specific aggregations with shared characteristics. To address the interconnected issues in these areas, this study aims to develop an SES prototype and analysis framework tailored for post-mining regions, based on the evolving Social-Ecological System Framework (SESF) [22]. This framework involves the following steps:

1. **System description:** Define the temporal and spatial scales of the SES framework; identify major social and ecological issues within various spatial scales of the post-mining area; determine key system components and organize multi-scale, nested system hierarchies.
2. **System dynamics:** Identify current and future changes, pressures, and disturbances, specifying vulnerability factors and their impact on the system and its components; conceptualize the evolution and feedback trajectories of each recovery phase as cycles of vulnerability and resilience.
3. **Governance actions:** Set desired system trajectories and corresponding action scenarios; investigate relationships and conflicts among stakeholders and institutions to clarify beneficiaries and executing agents.

3. Introduction

3.1. SES Analysis Framework for Post-Mining Landscapes

3.1.1. Temporal and Spatial Scale and Scope

The start time for restoration can be divided into three phases based on mine closure: restoration at closure, post-abandonment restoration, and progressive restoration. From the perspective of the entire recovery cycle, achieving a self-sustaining ecological state is a lengthy process requiring ongoing monitoring and intervention. The duration of the recovery phase varies depending on the ecosystem type, geographic and climatic conditions, and restoration methods; therefore, the endpoint of restoration is uncertain and may extend to ten years or longer. Most mines worldwide plan for closure and restoration near the end of their operational lifespan [23]. Restoration occurring at closure or after abandonment implies that mining activities have already caused large-scale damage to social and ecological systems, necessitating a longer restoration period. Progressive restoration, on the other hand, is an iterative process suitable for new or operational mines [23]. This approach involves establishing short-, medium-, and long-term closure plans throughout the mine's lifecycle, enabling restoration activities to proceed alongside production whenever feasible. Early closure efforts provide valuable lessons for subsequent restoration, with closure plans continually refined and updated during the process. Increasingly, governments and NGOs advocate for progressive restoration; however, this approach may not be applicable to already closed or specially mined sites and should be implemented under ideal conditions whenever possible.

The spatial scale and scope of restoration should be determined based on mining's impact on society and ecology. The development of some large cities and towns is closely linked to mining production and processing activities, especially in the case of non-metallic mines, such as limestone and clay mines, which supply raw materials for urban construction [24,25]. To reduce transportation costs, some mines are located near cities or major transportation routes, while others are situated in more remote areas [26]. At the territorial scale, the spatial distribution of mines influences social, ecological, and environmental factors across multiple levels [27]. Therefore, multi-scale spatial relationships must be considered when constructing hierarchical structures, with a focus on the cross-scale effects of system dynamics.

3.1.2. Main Issues and Challenges in SESs of Post-Mining Land

The social system, economic system, and human-environment interactions in post-mining areas face various challenges and issues (Table 1). Based on Table. 1, a prototype diagram is drawn to illustrate the relationships among affected elements and their spatial scales (Figure 1). The relational structure in the prototype diagram shows that mining's direct damage to the biophysical environment triggers a series of interconnected issues, which cascade into complex cause-and-effect chains.

It is important to note that each problem element has a different influence within the social-ecological system network. Ecological elements, through ecosystem services, broadly impact social elements, with factors such as finance, production and consumption, employment and livelihood, vegetation, and water quality being especially susceptible to other influences. Elements like topography, vegetation, and the built environment exert wide-reaching impacts across various aspects. Therefore, in post-mining restoration and management, identifying key functional nodes within the social-ecological system network is essential. These nodes play a crucial role in the overall function and stability of mining area systems, and interventions targeting these points can yield the most positive effects on system management.

Table 1. Main issues and challenges in post-mining area.

Systems	Subsystems	Elements affected	Issues and challenges	Reference
social system	Economy	Finance	Increased expenditure on environmental governance	[28]
		Production and consumption	Impacts food prices and food security; poses challenges to industrial transformation	[2]
		Employment and livelihoods	Rising unemployment and diversified livelihoods destruction	[29,30]
	Politics	Urban planning	Inhibits urban planning and development	[31]
		Social stability	Intensifies poverty, social unrest, and community alienation	[2,29]
	Habitat environment	Landscape visuals	Negative impact on landscape visual perception	[32]
		Built environment	Land encroachment; causes property and infrastructure damage	[33]
		Public health	Public Health Burden, lowers residents' quality of life	[34]
ecosystems	Terrestrial ecosystems	Biology	Biodiversity loss; affects food chains	[2,35-37]
		Vegetation	Vegetation damage	
		Soil	Taopsoil stripping; causes soil erosion, pollutant spread, or deposition	

		Air	Air pollution from dust and toxic gases	
		Topography	altered terrain and geomorphology	
		Landscape pattern	Landscape fragmentation caused by extensive land fragmentation and discontinuity	
	Aquatic ecosystems	Biomes	Reduced biodiversity; impacts food chain stability	
		Water quality	Heavy metal pollution; reduces water pH and chemical pollution; increases water turbidity.	
		Benthic environment	Altered substrate structure and microbial communities in water, sediment contamination.	
		Hydrology	Impacts on surface and groundwater permeability and runoff	
Human-environment interaction	Supply service	/	Resource supply disruptions; affects food, water, and raw materials	
	Regulatory services	/	Impediments to climate, hydrology, and air quality regulation, affects biodiversity conservation.	
	Support Services	/	Disruptions in water and nutrient cycles, impacts soil formation, primary productivity, and habitat integrity.	[38-40]
	Cultural service	/	Aesthetic and spiritual landscape value damage, limits recreational activities	

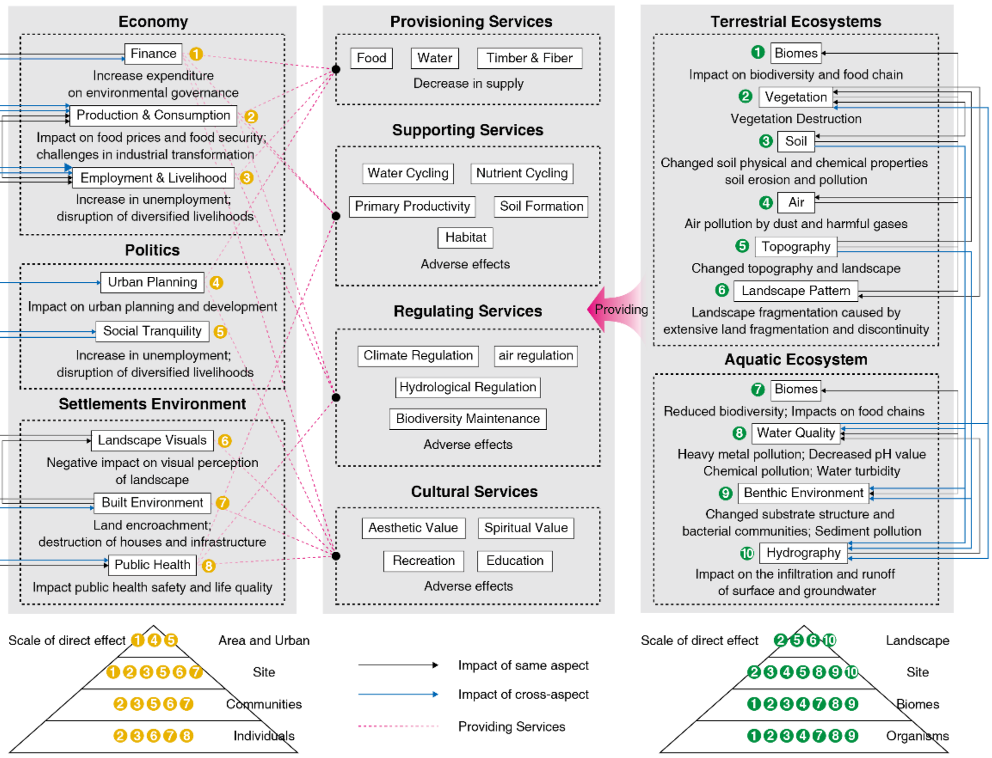

Figure 1. Main problems, interactions, and scales of impact in the post-mining area SES.

3.1.3. System Components and Hierarchical Structure

Identifying the components, hierarchical structures, and multi-level interactions within a mining area system helps diagnose the complexities of restoration and management. Based on Ostrom's SES framework, social-ecological system characteristics are broken down into nested and layered variables [13]. The social-ecological system framework for post-mining areas includes four main components: the Resource System, Resource Units (RU), Governance System, and Actors, each encompassing both ecological and social dimensions of the area (Figure 2). For example, the Resource System covers the ecological and geographical resources of the post-mining area along with various cyclical processes; Resource Units refer to specific resource elements such as soil, vegetation, and biodiversity; the Governance System includes the laws, policies, and institutions governing these resources; and Actors represent the stakeholders involved in the restoration, management, or use of these resources.

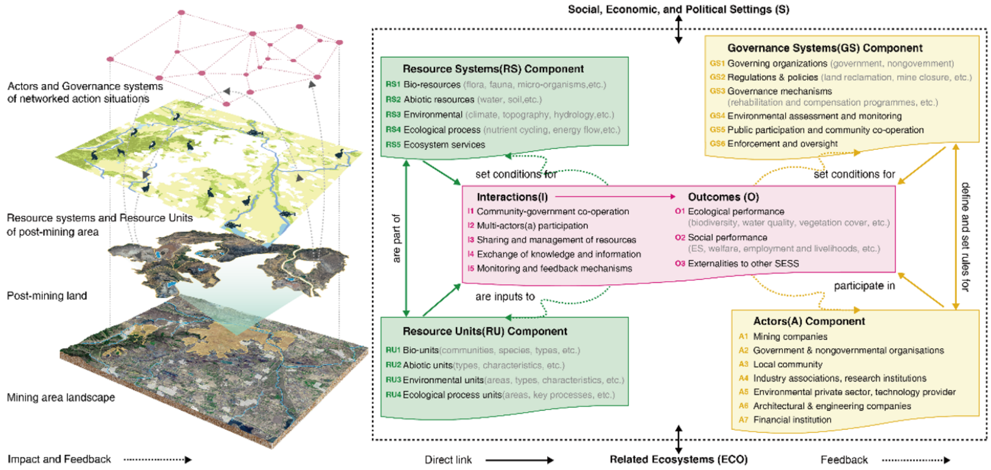

Figure 2. Components and hierarchical structure of the post-mining area SES.

3.2. System Dynamics

3.2.1. Driving Factors and Their Impacts

The restoration process in post-mining areas, driven by various complex issues, typically follows a phased yet iterative cycle: preliminary planning, risk assessment, engineering restoration, biodiversity reconstruction, land reuse, social transition, and post-monitoring and maintenance [23]. Throughout this process, restoration actions face multiple disruptive factors, which may negatively affect other parts of the system. Such socio-ecological disturbances can influence the Governance System or the Actors, potentially reducing the effectiveness of restoration efforts in post-mining areas (Table 2).

Referring to Table 2 and integrating the detailed content from Figure. 1 and Table. 1, a causal network is constructed to capture the impact of pressures and changes on the system. From an ecological perspective, soil, water quality, hydrology, vegetation, and habitats are sensitive elements prone to disruption. Among these, soil, water quality, hydrology, and vegetation, as Resource Units or parts of the Resource System, are key physical elements affected by disturbances. On the social side, production and consumption, employment, and livelihoods in post-mining areas are vulnerable to disruption, while fiscal economy and land use play critical roles in influencing restoration actions. These factors act as dynamic vulnerability nodes within the social-ecological system, highlighting the system's sensitivity and susceptibility to external shocks. A systematic assessment of these potential risks is essential to enable prompt and effective responses to adverse situations.

Table 2. Potential disturbances and changes in the post-mining area SES under governance actions.

The restoration stage	Action	Driving factors	Potential disruption or changes (ecological)	Potential disruption or changes (social)
Engineering restoration	Remove temporary water control structures and restore natural water circulation	Hydrography; production and consumption, public health	Affected by floods and water shortages, resulting in the deterioration of soil and water quality conditions	Generates pressure on water supply.
	Mechanized systems to treat mine water	Water; Production and consumption, public health	Under the continuous influence of pollution sources, seasonal floods, and droughts, leading to changes in communities	Affected by agricultural, industrial, and urban discharges, generating pressure on water supply
	Re-sloping, Drainage channels construction, Waste materials placement, covers placement	Soil; topography, hydrography, Soil; Landscape visualization, built environment, production and consumption	Affected by geological stability and waste disposal methods, causing geological changes and the deterioration of soil and hydrological conditions	Leads to environmental safety risks and creates pressure on water supply
	Conditioning of soil substrate and structure	Soil, water; production and consumption	Leading to the imbalance of soil matrix and structure, and changes in communities.	Affects agriculture and forestry
	Dust suppression, Eliminate sources of dust generation	Air, water; public health	Affected by extreme weather such as drought, resulting in chemical contamination.	Creates pressure on water supply and increases maintenance costs
Biodiversity reconstruction	Sowing, planting and propagation	Vegetation; production and consumption,	Influenced by water, soil, animal communities, and	Affects agriculture and animal husbandry,

		Landscape visualization	extreme weather, possibly introducing invasive species.	conflicting with land use and economic interests
	Species reintroduction, Habitat restoration	Terrestrial fauna; Production and consumption	Affected by extreme weather and human disturbances, leading to uneven species recovery and potential introduction of invasive species.	Conflicts with community and economic interests
	Water quality and hydrological management，Habitat restoration，Species reintroduction	Aquatic Fauna; production and consumption	Affected by extreme weather and human disturbances, causing ecosystem imbalance	Conflicts with land use and economic interests
Land reuse	Restoration to pre-mining land use or evaluation of alternatives	Production and consumption，employment and livelihoods，urban Planning	Influenced by land adaptability and ecosystem changes, potentially leading to further ecological degradation	Affected by economic feasibility, conflicting with current land use and economic interests
Social transition	Promote agriculture or tourism, implement employee retraining programs, support local small businesses, and enhance self-management capacity of communities, etc	Production and consumption，employment and livelihoods，social stability	Influenced by land adaptability and ecosystem changes, potentially leading to further ecological degradation	Affected by community conflicts, social structure changes, and population migration, leading to employment issues, economic restructuring difficulties, and social instability

3.2.2. Cycle of Vulnerability and Cycle of Resilience

The vulnerability and resilience cycles represent two distinct response modes within social-ecological systems (SES) when facing disturbances and pressures. Building a framework around these cycles deepens the understanding of how vulnerable components in post-mining areas adapt and transform. These cycles coexist and interact within the SES framework, shaping the trajectory of system recovery and transformation.

As illustrated in Figure. 3 with the example of mine vegetation restoration, the resilience cycle emphasizes holistic recovery and long-term goals but requires more time, which may result in substantial short-term losses. In contrast, the vulnerability cycle focuses on quick solutions to isolated problems; however, measures aimed at reducing short-term losses might undermine long-term resilience. Therefore, integrating the complementary aspects of vulnerability and resilience is essential:

1. **Balancing Short-term and Long-term Goals:** Short-term goals focus on emergency responses to ensure environmental safety and basic infrastructure for mining communities. Long-term goals aim at comprehensive ecosystem restoration and sustainable social development, enhancing the ecosystem's self-healing ability and resilience against future risks in post-mining areas.
2. **Diversity and Redundancy in Resources and Pathways:** Diversity underpins a system's capacity for self-organization by providing alternative pathways and enhancing adaptability in the face of uncertainty. This diversity allows for flexibility and a range of options as ecological and social conditions change.
3. **Collaboration Among Governance Systems and Actors:** Engaging multiple stakeholders facilitates the integration of resources and knowledge across different levels, promoting more effective adaptive strategies.

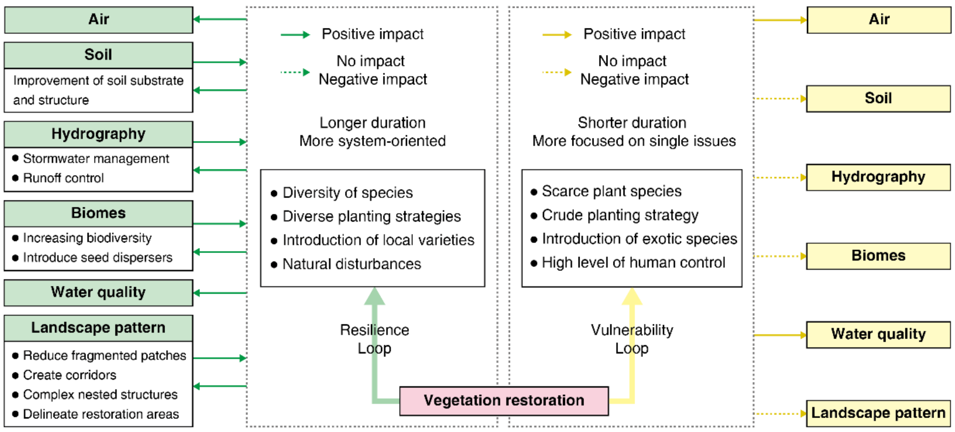

Figure 3. Feedback loop of resilience and vulnerability (an example of vegetation restoration).

3.3. Governance Action Framework

When constructing a governance action framework, applying an Actor-Network System (ANS) allows researchers and policymakers to better understand the interactions and impacts among governance actions. This network analysis helps simulate potential conflicts and collaboration opportunities, optimize resource allocation, and support the development of more effective governance strategies [41].

For instance, in vegetation restoration, the actor network shown in Figure 4 identifies the main participants involved in restoration activities [42-44]. Each actor contributes distinct roles and interests to the recovery process. Contextual elements such as policies, regulatory oversight, implementation mechanisms, and feedback loops connect these actors, shaping their decisions and behaviors [45,46]. The actor network reveals collaborative relationships within governance actions, where outcomes of specific actions may influence other pathways in the network.

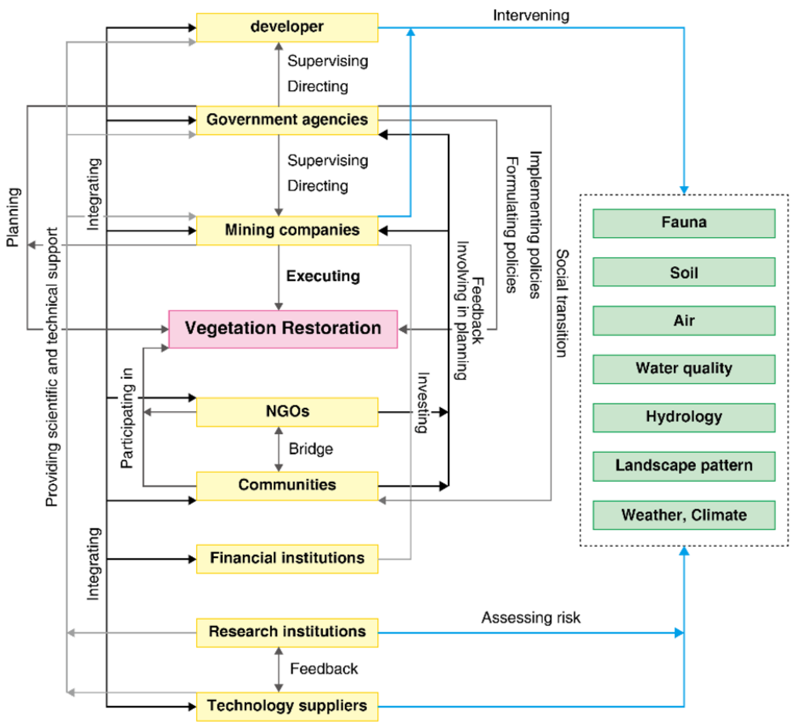

Figure 4. Actor network of post-mining governance (an example of vegetation restoration).

Visualizing the actor network clarifies the influence of actors in both cooperative and conflict scenarios [47]. Key nodes in this network—such as mining companies, government departments, and local communities—play central roles in information flow, resource distribution, and coordination of decision-making [48]. Dysfunction in these core nodes can trigger cascading governance inefficiencies, undermining both the timeliness and strategic coherence of decisions [49].

Therefore, it is crucial to assess conflict risks during restoration planning, identify optimal collaboration strategies, and enhance implementation efficiency. Special attention should be given to ensuring redundancy and stability of core nodes when designing and maintaining governance structures [50].

4. Conclusion and Discussion

This study explores restoration and reconstruction models for post-mining areas based on social-ecological systems (SES) theory. It proposes a comprehensive, interdisciplinary framework that integrates ecological recovery with socio-economic revitalization to promote sustainable land use in these areas. The research identifies key issues and challenges faced in post-mining regions, establishes an SES hierarchy, and models optimal stakeholder actions by analyzing system vulnerabilities and integrating complementary aspects of vulnerability and resilience. The guiding principles include:
(1) Defining temporal and spatial boundaries across multiple scales;
(2) Assessing critical system vulnerabilities;
(3) Aligning short-term emergency responses with long-term development goals;
(4) Maintaining resource diversity and redundancy;
(5) Enhancing stakeholder engagement and network connectivity.

The study finds that effective post-mining restoration depends on the mutual reinforcement and integration of ecological and social systems, which requires stakeholder collaboration, cross-scale governance, and adaptive management strategies. Ecological restoration generally progresses slowly, while socio-economic recovery is often more vulnerable to external influences, highlighting the need to maintain a dynamic balance between the two in practice.

Post-mining reconstruction is inherently interdisciplinary, and one-dimensional approaches cannot adequately address the complexity of these systems. The framework presented here calls for further refinement and expansion to provide actionable insights for sustainable development policies in post-mining areas. Future research should expand SES assessment dimensions, incorporate remote sensing and data analytics to better quantify social and ecological components, and explore sustainability challenges across diverse social-ecological contexts in post-mining regions.

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