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REVIEW

Environmental Stress and Carbon Storage Optimization in Mining-Driven Land Use in Northern Shaanxi

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ABSTRACT

This review synthesizes advances in simulating environmental stress effects and coordinating carbon storage optimization within mining-driven land use evolution, with a focus on the Shaanxi Northern Mining Area Basin. Intensive coal exploitation reshapes land use/land cover patterns through excavation, subsidence, waste dumping, and infrastructure expansion, while simultaneously intensifying coupled stresses such as soil degradation, vegetation loss, hydrological disruption, and erosion. We summarize how recent land system modeling has progressed from static suitability constraints toward dynamic, spatially explicit frameworks that incorporate stress indicators and, increasingly, feedbacks between environmental processes and land conversion. We then assess approaches for quantifying carbon storage under mining disturbance, ranging from coefficient-based carbon accounting to ecosystem service and process-based models, emphasizing uncertainty sources linked to land classification, carbon density heterogeneity, and scale mismatch. Building on these foundations, we review coordinated optimization strategies that integrate carbon storage objectives with land demand and environmental constraints through multi-objective and scenario-based methods. Such frameworks reveal context-dependent trade-offs and synergies among mining development, reclamation, and ecological restoration, and carbon sequestration potential, particularly under water-limited and erosion-prone conditions. Finally, we identify research priorities for mining basins, including tighter coupling of stress, carbon, and land dynamics, improved representation of socio-economic decision-making behavior, long-term monitoring and validation, and uncertainty-aware decision support. These directions can strengthen low-carbon, resilient land use planning in ecologically fragile mining regions.

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1. Introduction

The rapid worldwide energy and mineral resource demands have radically changed land systems, especially in areas where intensive mining practices are predominant. The change in land use and land cover (LULC) caused by mining has turned out to be one of the most significant contributors to the degradation of the ecosystem, distorting the surface structure and hydrological processes, changing soil properties, and vegetation dynamics [1]. Such disturbances are frequently enhanced in ecologically vulnerable areas like arid and semi-arid regions, in which background environmental stressors like water scarcity, soil erosion, and climate variability tend to amplify the ecological effects of such disturbances. The relationships between environmental stressors and the mining-driven evolution of land use and the role of these interactions on the functioning of the ecosystem, including carbon storage, have thus emerged as a major scientific and policy concern [2,3].

One of the most significant coal production bases in China and a typical region ecologically in danger because of mining is the Shaanxi Northern Mining Area Basin. The last several decades have been characterized by massive land use changes necessitated by coal production, related industrial infrastructure development, and population agglomeration, which include the increase in mining land use, industrial land use, and construction land use, with coinciding breakdown and deterioration of the grasslands, croplands, and forest ecosystems. These modifications have been taking place against the background of a geomorphology of loess, scarce water sources, and great responsiveness to climatic and anthropogenic stress. Consequently, mining activities, environmental stress, and land system development are highly intertwined phenomena, and the basin has become the perfect place to study them [4–6].

The stress of the environment in the mining zones is not a phenomenon of one factor but the result of a combination of various interacting factors. Mining, whether underground or open pit, may cause land subsidence, cracks on the surface, and damage to the soil structure, and water-intensive mining activities may tend to worsen groundwater depletion and break the surface hydrology. The decline of vegetation and soil erosion increases the threat of erosion and desertification, decreasing the resilience of the ecosystem. The combination of these stressors affects land use paths, limiting the suitability of land, modifying the interactions between human actions and natural ecosystems, and transforming the spatial patterns of land transformation. Conventional tests, which involve only land use change or individual stresses of the environment, might thus fail to capture the overall and interactive outcomes of mining-induced stress to regional ecologies [7,8].

Carbon storage is included among the ecosystem services that have been influenced by the evolution of land use, as it has become the focal point of climate regulation and the development of carbon-neutrality and low-carbon agendas. Carbon sinks. Land systems are carbon intermediaries and depend on land cover type, land management practices, and disturbance regimes to be carbon sinks or carbon sources. The mining activities normally cause high amounts of carbon waste through the destruction of vegetation and soil carbon and the degradation of the ecosystem in the long run. Nonetheless, land recovery, ecological reconstruction, and efficient planning of land use also provide a possibility of increased carbon sequestration and some compensation for the mining-related emissions. The factual quantification of the carbon storage dynamics under a mining-induced change of land use, particularly in conjunction with environmental stress, is an important scientific difficulty [9,10].

Over the past few years, there have been developments in spatial modeling, remote sensing, and integrated assessment models that have facilitated complex simulations of land use change and ecosystem activities. Land use evolution coupled with environmental stress indicators, including water stress, soil erosion, and vegetation degradation, has models that offer a way to examine how stress factors influence future land system paths. Meanwhile, the ecosystem service models have been extensively used to approximate spatially explicit carbon storage and its response to land use changes. In spite of these methodological developments, current studies usually deal with environmental stress simulation as well as carbon storage assessment on their own without much integration between the two. In addition, much of the analysis is descriptive and historical change as opposed to exploring coordinated optimization paths as part of future development and environmental limits.

An integrated optimization of land-use development for carbon storage is a promising method of balancing the aims of resource extraction, ecological protection, and mitigation of the climate in the mining areas. Through the incorporation of carbon storage goals into any land use simulation and optimization model, there is a possibility of determining the spatial arrangements and management approaches that would reduce the level of ecological degradation and still allow the required socio-economic activities. Such frameworks may be better able to represent real-world constraints and trade-offs when environmental stress effects are explicitly included, demonstrating relationships between synergies and conflicts between mining development, ecosystem resilience, and carbon sequestration capacity. The latter is especially significant in directing the sustainable management of land and the formulation of policies that are ecologically sensitive to delicate basins [11].

It is against this context that a comprehensive study of simulations of the effects of environmental stress and the systematized or orchestrated optimization of carbon storage within the system of mining-induced land use evolution is a timely and desirable undertaking. Based on the Shaanxi Northern Mining Area Basin, this article is a synthesis of the available literature on (i) the nature of mining-induced environmental stress and land use change, (ii) modeling strategies to simulate the effects of the stresses on land systems, (iii) the strategies to estimate carbon storage under land use evolution, and (iv) optimization strategies that combine carbon storage goals under environmental constraints. Critical assessment of existing methodologies, addressing the gap in knowledge, and pointing to future research opportunities, this review will contribute to the further development of integrated land system science in mining areas and help to create low-carbon and resilient land use pathways [12,13].

Finally, we should enhance our knowledge of the interaction of environmental stress and mining processes to determine the evolution of land use and the storage of carbon in the environment to enable the regional sustainability of northern Shaanxi and other resource-intensive basins with similar problems in other parts of the world. The review aims to provide a conceptual and methodological basis for future research that can transcend fragmented analyses of sustainable management of mining landscapes into decision-oriented approaches of the latter.

2. Environmental Stress Factors and Land Use Evolution Driven by Mining Activities

Mining operations essentially change land regimes through the creation of robust and enduring anthropogenic disruptions that interrelate with a set of natural environmental limitations. The effects of these disturbances in ecologically sensitive areas are not individual but rather lead to a cascade of environmental stress reactions that have an impact on land use evolution over time. The Shaanxi Northern Mining Area Basin has reached the stage where intensive coal exploitation has become a powerful force that can lead to the change of the land system, and it is necessary to investigate the nature of the mining-induced environmental stress and how it influences land use dynamics [14].

2.1. Characteristics of Mining-Induced Environmental Stress

In mining areas, there is environmental stress caused by the direct disturbance of the land as well as the indirect ecological feedback. Massive underground and open-pit mining changes the surface morphology due to excavation, dumping, and subsidence, consequently causing landscape fragmentation and a lack of land stability. These physical disturbances interfere with the soil structure, increase the rate at which soil erodes, and decrease the ability of the land to sustain vegetation regeneration. Surface disturbance due to mining can very quickly increase land degradation in loess-covered regions whose inherent soils are prone to erosion [15].

Another characteristic feature of mining areas is hydrological stress. The mining of coal can also require a significant amount of groundwater drainage, leading to dwindling water levels and changes in surface-groundwater interactions. Decreased availability of soil moisture limits vegetation development and agricultural yields, and variations in runoff routes may exacerbate soil erosion and sediment movement.

Mining-related water stress may greatly enhance ecological vulnerability and the risk of land use in semi-arid basins, where water resources already constrain the functioning of the ecosystem [16].

Besides the physical and hydrological stress, mining works cause long-term ecological stress due to vegetation clearing, fragmentation of habitats, and pollution. Soil contamination, dust emissions, and solid waste not only worsen the quality of the land but also prevent natural succession. These stress factors have synergistic effects and result in cumulative effects beyond specific mining sites, affecting the regional land systems [17–19]. **Table 1** summarizes the key environmental stress factors caused by mining activities and their implications on land systems and carbon storage.

Table 1. Major environmental stress factors induced by mining activities, their primary sources, affected land system components, and implications for land use evolution and carbon storage.

Environmental Stress Factor	Primary Mining Source	Affected Land System Components	Typical Land Use Impacts	Implications for Carbon Storage
Soil degradation	Excavation, dumping, and subsidence	Soil structure, nutrients	Reduced land suitability for agriculture and restoration	Accelerated soil carbon loss
Hydrological stress	Groundwater drainage, water consumption	Groundwater, surface runoff	Vegetation decline, land abandonment	Suppressed biomass carbon accumulation
Vegetation degradation	Land clearing, dust deposition	Plant cover, productivity	Conversion to low-ecological-function land	Immediate aboveground carbon loss
Land subsidence	Underground mining	Surface morphology	Fragmentation, formation of subsidence land	Long-term carbon recovery constraints
Pollution stress	Waste piles, emissions	Soil and vegetation quality	Persistent degraded land use	Inhibited carbon sequestration

2.2. Mining-Driven Land Use and Land Cover Change Patterns

Long-term mining processes cause a significant spatial and temporal change in land use and land cover patterns. The mining land, industrial land, and related infrastructure usually increase at the cost of natural and semi-natural land covers, including grasslands, croplands, and woodlands. The new types of land use that emerge due to subsidence zones and the land left from mining have low productivity and a high ecological threat. These transformations tend to be discontinuous and piecemeal in nature, redefining the landscape structure and connectivity.

The evolution of land use in the Shaanxi Northern Mining Area Basin is indicative of the severity of mining operations in the region as well as of the developmental policies of the area. The coal economy has also been associated with rapid industrialization and urbanization, which have stimulated the growth of construction land and ecological restoration programs, leading to localized recovery of vegetation in chosen areas. The co-presence of land degradation and restoration forms a heterogeneous land use mosaic, with one side of land use change coexisting with the other land use change under alternative management regimes.

A temporal study of land use change indicates that transitions caused by mining are, in most cases, irreversible within the short to medium term. After land has been turned into a mine or an industry, it becomes hard to recover its original ecological condition, as there is continued degradation of the soil, the hydrology, and continued disturbance. This path dependency suggests that it is important to know the dynamics of land systems over a long time and not just the short-term rates of land use changes [20–22].

2.3. Interactions Between Environmental Stress and Land Use Evolution

Environmental stress has a dual effect on the evolution of land use in that it facilitates and limits land use change. On the one hand, mining operations actively cause stress, which affects the land quality and the resiliency of the ecosystem, and thus leads to an increase in the rate of land conversion to low-ecological-function use. Conversely, growing environmental stress influences land use decision-making as it restricts land use to agriculture, settlement, and ecological regeneration.

As an example, soil erosion and water shortages decrease the viability of some of the more traditional land uses, such as rain-fed agriculture, and some shift to industrial or deserted land uses in regions of severe stress. On the other hand, policy-directed ecological restoration initiatives are frequently geographically focused on regions where stress levels have not been exceeded, strengthening unbalanced land utilization development throughout the basin. Complex non-linear interactions between environmental stress intensity and land use transitions are developed through these feedback mechanisms.

The mediation of stress and land use is also influenced by socio-economic processes, such as the intensity of mining, technological activities, and governance systems. Regions more concentrated on environmental management and reclamation are characterized by a more balanced land use development process, whereas regions characterized by large-scale mining are characterized by a steady accumulation of stress and environmental deterioration. Such interactions are very important to understand when simulating the future land use trajectories in mining regions [17,23].

2.4. Implications for Ecosystem Function and Regional Sustainability

The interactive effects of environmental stress due to mining and land use evolution have far-reaching consequences on how an ecosystem operates. Degradation of plant cover and soil fabric lowers primary productivity and undermines the land system's provision of ecosystem services to the environment, including carbon storage, water regulation, and erosion control. As mining and construction land is taken over by land use, ecosystem functions are more fragmented and uneven in their spatial distribution [24].

Regarding the idea of sustainability at a regional level, environmental accumulation in an unmanaged way can predetermine land systems in the direction of degradation, which is hard to prevent. This not only endangers ecological security but also compromises the socio-economic sustainability of the mining areas in the long run. Environmental stress as a key concern in land use evolution also offers grounds for integrated approaches in modelling that involve linking land use change to ecosystem service dynamics, as well as optimization strategies. In this regard, the detailed knowledge of environmental stressors and mining-induced land use changes is a precondition for the modeling of the future and providing coordinated land use plans that would help strike a balance between resource exploitation and environmental conservation and carbon sequestration [25,26]. The coupled mechanisms linking mining activities, environmental stress generation, and land use evolution are synthesized conceptually in **Figure 1**.

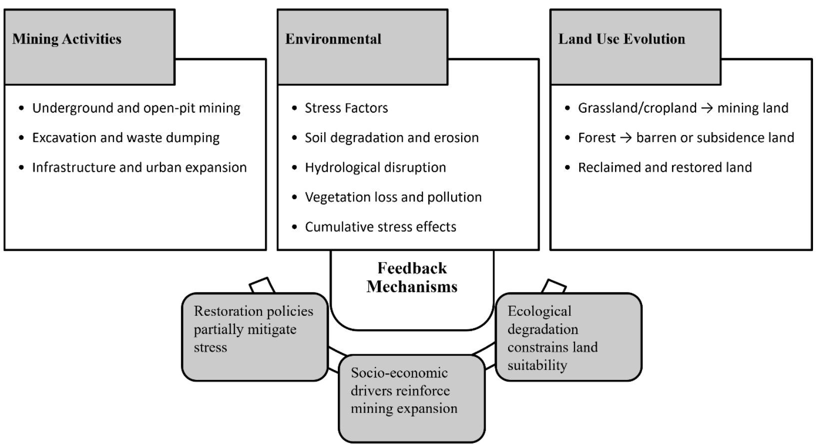

Figure 1. Conceptual framework illustrating interactions among mining activities, environmental stress factors, land use evolution, and feedback mechanisms in mining-affected land systems.

3. Simulation Approaches for Environmental Stress Effects on Land Systems

Environmental stress effects simulation offers a fundamental methodology for the comprehension and prediction of land use development in mining areas. Since the land system change associated with mining is a result of the interaction of human activity and biophysical constraints, the simulation methods should be able to capture the anthropogenic decision-making process as well as the environmental feedback process. In the last twenty years, the spectrum of modeling frameworks has been created to include the impacts of environmental stress on land suitability, land conversion processes, and spatial land use patterns to provide useful information regarding the dynamics of mining-impacted landscapes [27,28].

3.1. Conceptual Frameworks for Simulating Environmental Stress

On the conceptual level, environmental stress is normally modeled as a constraining or adjusting variable in land system models. The changes in the abilities of land caused by stress to support certain activities are to decrease the ecological appropriateness, increase the likelihood of degradation, or limit resources. The causes of stress occur in mining regions in a multi-faceted manner through various channels, such as degradation of soil, disruption of hydrology, and loss of vegetation, and in some cases, these are all interdependent. Coupled human-environment systems are thus increasingly highlighting simulation frameworks where land use choices are dynamically responsive to changing environmental factors [29,30].

Initial simulation research tended to model the environmental variables as background constraints, which did not change with time: climate, soil, and hydrological conditions were held constant. Nevertheless, in mining areas, environmental stress is a dynamic process that is coupled with land use change, which involves models that can handle feedback processes. Slightly more modern methods explicitly incorporate stressors in land use transition regulations, such that environmental degradation or recovery can affect the future likelihood of land conversion. Such a change to dynamic stress representation has been recognized to make land system simulations in disturbed landscapes far more realistic [31].

3.2. Land Use Change Models Incorporating Environmental Stress

Several models of land use change have been used to simulate land evolution caused by mining under environmental stress conditions. The reason why cellular automata-based models have been extensively utilized is their capability to capture the effects of the neighborhood and spatial interactions, which are relevant especially in fragmented mining landscapes. These models can be used to simulate the suppression of the growth of ecologically sensitive land use by environmental stress indices, with the encouragement of the growth of mining or abandoned land by embedding environmental stress indices in the transition rules.

The spatially explicit land allocation models also focus on land suitability and competition between land use types. In these models, the stress factors in the environment would be converted to penalties on suitability that make a particular land use less attractive in areas of stress. Such a strategy fits well with the concept of examining spatial land use patterns at the regional scales, as cumulative stress alters them. But it can simplify the intricate feedback between the evolution of stress and land management practices in cases where stress is considered an exogenous factor instead of an endogenous process [27,32].

Process-based models and hybrid models will aim to curb this gap by connecting land use change and ecological or hydrological sub-models. Such frameworks enable the stress variables (soil moisture or the intensity of erosion) to respond to the change in land use, with two-way feedback between land systems and environmental processes. Such models may have a greater explanatory power, but they also demand a large amount of data and calibration and can therefore be problematic in data-sparse regions of mining. **Table 2** compares and contrasts representative simulation models designed to characterize mining-induced land use change due to environmental stress, and their advantages and disadvantages [33–36].

3.3. Quantification and Spatialization of Environmental Stress

The credible quantification and geometry of stress indicators are what is required in the accurate simulation of environmental stress effects. The stress measures that are commonly applied are soil erosion intensity, water stress indices, vegetation degradation indicators, and composite ecological vulnerability indices. These indicators can be obtained as the resulting product of remote sensing data, field measurements, and model results, allowing the stress to be mapped in space on a continuous basis.

Table 2. Comparison of major land use simulation models incorporating environmental stress effects in mining regions.

Model Type	Core Characteristics	Representation of Environmental Stress	Strengths	Limitations
Cellular automata–based models	Grid-based, neighborhood interactions	Stress embedded in transition rules	Strong spatial dynamics	Limited process realism
Land allocation models	Suitability- and demand-driven	Stress as a suitability constraint	Clear land competition logic	Weak feedback mechanisms
Process-based models	Biophysical process simulation	Dynamic stress–process coupling	High explanatory power	High data and calibration demands
Hybrid models	Combined spatial and process elements	Partial two-way feedbacks	Balanced realism and scalability	Model complexity

In mining regions, remote sensing is especially useful as ground-level surveillance can be restricted. Vegetation loss, land subsidence proxies, and surface disturbance that can be translated to stress gradients can be detected using time-series satellite data. These spatial stress layers that are included in land use simulation models are useful in constraining land conversion in highly degraded regions, as well as in the description of heterogeneity in land system responses.

Irrespective of these developments, there are still uncertainties in the quantification of stress. Various indicators can serve as different measures of environmental stress, and their relative significance in different land use systems and spatial scales can differ. Besides, there are also stress limits beyond which land use cannot be maintained; such limits are usually hard to delimit. These ambiguities spread with the simulations, and they have to be closely taken into account when constructing the model output [37].

3.4. Integration of Socio-Economic Drivers and Environmental Constraints

The credible quantification and geometry of stress indicators are what is required in the accurate simulation of environmental stress effects. The stress measures that are commonly applied are soil erosion intensity, water stress indices, vegetation degradation indicators, and composite ecological vulnerability indices. These indicators can be obtained as the resulting product of remote sensing data, field measurements, and model results, allowing the stress to be mapped in space continuously [38,39].

3.5. Limitations and Challenges in Stress-Based Land System Simulation

Although much has been achieved, the simulation methods that are currently used have a number of limitations when they are used in mining areas. Agreement should be maintained due to a scale mismatch between land use decisions and environmental processes, especially in cases where fine-scale stress processes are combined with regional land use models. Inadequacy of data and uncertainties further limit model calibration and validation, particularly of groundwater depletion and land subsidence processes at the subsurface.

Further, most of these models are based on recreation of historical land use patterns as opposed to investigating adaptive or optimized futures that are environmentally constrained. Consequently, they have limited ability to signal sustainable land management and optimization that is carbon-oriented. To avoid such challenges, more integrated systems must be used that would integrate environmental stress simulation with land use optimization and ecosystem service assessment [40,41].

In general, environmental stress methods have been developed over the years as the method has shifted to being more dynamic and integrated, compared to the conventional constraint-based models. These advances give a methodological approach to associating land use development caused by mining with the outcome of ecosystem carbon storage, which is explored in the following sections.

4. Carbon Storage Assessment under Mining-Driven Land Use Change

The storage of carbon is a fundamental ecosystem activity that indicates the ability of land systems to control climate by sequestration and retention of carbon in vegetation and soils. Change in land use due to resource mining in the mining regions creates powerful and sometimes sudden effects on carbon processes, converting carbon sinks into net carbon sources. To measure carbon storage in the context of the evolution of land use due to mining, it is necessary to employ methods that will enable the measurement of both the direct impact of the conversion of the land cover and the indirect impact of environmental stress on the processes in the ecosystem [13].

4.1. Linkages between Land Use Evolution and Carbon Storage Dynamics

The change in land use and land cover essentially transforms the structure and functioning of terrestrial ecosystems, thus redefining the patterns of carbon storage. Turnover of grassland, cropland, or forest to mining land or construction land usually leads to instantaneous losses of aboveground biomass carbon and soil organic carbon depletion over the long term. The occurrence of these losses is usually increased by soil disturbance, soil compaction, and soil erosion during the mining process, which leads to a high level of carbon mineralization and a decrease in carbon accumulation capacity.

The development of land use in mining regions is often fragmented and heterogeneous, resulting in a carbon storage distribution that is spatially uneven. The carbon recovery even after mining is discontinued may be limited by subsidence areas, waste heaps, and barren mining areas, which still have low soil fertility and little vegetation cover. On the other hand, reclaimed or ecologically restored areas may regain their carbon sequestration ability over time, depending on the intensity of the restoration, the species composition, and the environmental conditions. Consequently, the carbon storage processes in the mining areas show a balance between gains of disturbance loss over time and gains of management loss over time [42].

4.2. Methods and Models for Carbon Storage Assessment

Various approaches have been developed to estimate carbon storage in land use change, and the approaches have different complexities, data requirements, and levels of spatial resolution. Linear methods with land cover-specific carbon density coefficients are very common in studies at a regional scale because of their simplicity and integration ability with land use maps. These techniques approximate carbon storage by averaging the carbon densities of various land use types and summing them spatially to give a first-order approximation of carbon stocks and their variations as a result of changes in land use.

The process-based and ecosystem productivity models provide a more in-depth insight into carbon dynamics since they model the growth of vegetation, litter input, and soil carbon turnover. These kinds of models can model the impact of environmental stress, such as water shortage or soil erosion, on carbon flux. Nevertheless, they are frequently used in mining areas with limited access to long-term ecological and soil data and parameters to be used in disturbed land covers.

Explicit ecosystem service models. Spatially explicit ecosystem service models have been applied more frequently to evaluate carbon storage under land use change, including models created within the Invest framework. These models are a combination of land use maps and carbon pool data to determine aboveground, belowground, soil, and dead organic matter carbon. They can be combined with geographic information systems, and, therefore, carbon storage patterns can be visualized, and the areas of high and low carbon in mining landscapes can be noted. Although such models give a reasonable tradeoff between complexity and geographical detail, they usually presume constant carbon densities and might not adequately represent dynamic behavior at times of persistent environmental attack [43].

4.3. Carbon Pool Responses to Mining Disturbance and Environmental Stress

The various carbon pools do not react to the land use change and environmental stress caused by mining in the same manner. Carbon in the aboveground biomass is generally the most sensitive compartment and suffers fast loss after vegetation clearance, and can be slowly regained through reclamation. The carbon pools of the soil and below-ground biomass have a higher inertia, but this may change dramatically in the long term in the case of soil structure destruction or increased soil erosion. These responses are mediated by environmental stress. Water stress reduces net primary productivity and growth of plants, as well as carbon input to both biomass and soil pools, which is limiting. Erosion of soil only removes the rich carbon topsoil, and thus, the loss of carbon becomes irreversible and decreases the efficacy of the restoration process. These stressors may inhibit the buildup of carbon even in cases where land use shifts toward ecological restoration in arid and semi-arid mining areas; this suggests that stress impact should be considered in carbon evaluation [17,34].

Heterogeneity in carbon storage is further increased by the intensity of stress, which is spatially different. Regions with extensive subsidence or a long-lasting water shortage tend to be low-carbon terrain, whereas regions with more or less normal soil and hydrology can be used as small carbon reservoirs. The spatial patterns are critical in determining priority areas for carbon-oriented land management.

4.4. Uncertainty and Scale Issues in Carbon Storage Estimation

The assessment of carbon storage in land systems that are driven by mining faces various sources of uncertainty. The variation in the carbon density values among types of land use, the variation in model structure, as well as inconsistencies in the classification of land use, may all affect the estimated carbon stock. The challenge of carbon accounting is additional in mining areas since there are sudden land use changes and the development of new land covers, including reclaimed or partially restored lands.

There is also the problem of scale mismatch. Carbon processes have fine temporal and spatial scales, whereas land-use change analyses are typically performed at coarse-resolution time scales. The loss or gain of carbon in both localized and regional estimates can be hidden by the aggregation of heterogeneous land parcels, and as a result, biased estimates can be drawn. Furthermore, most of the assessments concentrate on carbon storage snapshots, ignoring the dynamic aspects of carbon storage through disturbance and recovery events. The only way of dealing with such uncertainties is to carefully choose the model, conduct sensitivity analysis, and, in cases where feasible, reconcile the field observations with the remote sensing and model outputs. Clear identification of uncertainty is especially essential where carbon storage evaluation is applied in making policy decisions and land use optimization in mining areas. **Table 3** provides a summary of popular techniques for carbon storage evaluation under mining-induced land use change, their data needs, and the capability to indicate environmental stress [13,44,45].

Table 3. Methods for assessing carbon storage under mining-driven land use change and their capacity to represent environmental stress effects.

Method Category	Main Inputs	Carbon Pools Considered	Ability to Reflect Environmental Stress	Typical Application Scale
Carbon density coefficient method	Land use maps, carbon coefficients	Biomass, soil	Low	Regional
Ecosystem service models	Land use, carbon pool data	Biomass, soil, dead matter	Moderate (indirect)	Regional to basin
Process-based carbon models	Climate, soil, vegetation data	Full carbon cycle	High	Site to regional
Remote sensing–assisted estimation	Vegetation indices, land cover	Mainly biomass	Moderate	Regional

4.5. Implications for Carbon-Oriented Land Management in Mining Regions

Evaluation of carbon storage during land use change under mining offers very important information on the climatic effects of resource extraction and how this effect can be mitigated by land management. Carbon storage evaluations aid in the determination of areas of concern where carbon is lost to ensure that these areas are priority zones for restoration and for the distribution of scarce ecological resources. Combined with land use simulation and environmental stress analysis, these assessments provide a platform for the coordinated optimization strategies of mining development to balance carbon sequestration goals and mining development.

In a mining basin where the pressure to keep in line with carbon neutrality requirements is ever rising, the incorporation of sound carbon storage evaluation in land use planning is now a requirement rather than a choice. The elucidation of the mechanisms, the spatial patterns, and the uncertainty of the change in carbon storage is one of the required steps in the design of sustainable pathways of land use under continuous environmental pressure [46].

5. Coordinated Optimization of Land Use and Carbon Storage under Environmental Constraints

The concerted land use and carbon storage optimization has become one of the decisive strategies to overcome the multitude and frequent contradictions of the goals existing in mining areas. Compared to the traditional land use planning methodology that relies on economic production or immediate land demand, coordinated optimization clearly attempts to balance resource extraction, ecological preservation, and mitigation of climate within the limitations of environmental stress. Such optimization frameworks offer a way out of increasingly unsustainable and fragile land system configurations in mining-based landscapes where land degradation and carbon loss go hand in hand [47–49].

5.1. Conceptual Basis of Coordinated Optimization in Mining Regions

The key concept of coordinated optimization is the understanding of land use as a multifunctional system that is able to provide economic, ecological, and social benefits at the same time. Land is not only the bearer of industrial activity in mining lands, but also a significant element of the ecological security of the region and carbon control. The coordinated optimization thus demands the combination of various goals, such as the fulfillment of the land demand for mining and the development thereof, the reduction of the accretion of environmental stress, and maximizing or stabilizing the carbon storage.

The environmental constraints are a major factor in determining the possibility of the optimization effect. The lack of water, soil erosion, and ecological fragility impose certain limitations on some land use changes and lower the efficiency of restoration actions. The introduction of these limitations makes the optimization models go beyond idealized land allocation scenarios and more towards realistic trade-offs and thresholds. The method is especially applicable to mining basins that are ecologically delicate, such that over-exploitation of the environment can lead to permanent and irreversible land degradation [50].

5.2. Multi-Objective Optimization Approaches for Land Use and Carbon Storage

Multi-objective optimization methods are common to balance between conflicting land system outcomes. These strategies generally characterize the idea of carbon storage as one of the primary goals, in addition to economic returns, land use demands, or ecological risk reduction. Instead of maximizing one outcome, optimization algorithms are used to find land use configurations that will provide acceptable trade-offs between objectives.

Carbon-oriented optimization used in mining areas tends to focus on both the high-carbon land type preservation and the optimal location of the land used in restoration to increase the sequestration potential. The indicators of environmental stress are imposed to penalize land conversions in very degraded or water-stressed areas, and hence direct land use towards more appropriate areas. The resulting patterns of land use are likely to be characterized by a concentration of mining activities in regions that are relatively less sensitive to ecological factors and by the encouragement of vegetation recovery in areas with high restoration potential.

Nevertheless, the results of optimization are very prone to the options of goals, constraints, and weighting plans. Excessive focus on carbon storage can be inconsistent with short-term economic concerns, and a lack of focus on environmental stress can result in unrealistic land-use distribution. Balanced optimization is not easily achieved, thus necessitating the competent design of models and the clear expression of planning priorities [51].

5.3. Scenario-Based Optimization under Mining and Restoration Pathways

Scenario analysis is typically employed to learn about coordinated optimization along other development and management paths. Examples of these are normal expansion of business-as-usual mining, reinforced ecological repair, and policy-based low-carbon shifts. By comparing optimised land use results under various conditions, researchers can test the effect of alternative assumptions on mining intensity, environmental regulation, and restoration investment in carbon storage and the resilience of land systems [52].

In mining-based contexts, optimization can be aimed at reducing carbon waste through reducing the spatial area of mining land and reclamation in highly disturbed regions. Restoration-oriented situations, on the other hand, usually stress the growth of grassland or forest cover in moderately stressed areas, which may help increase carbon sequestration and also ecological stability. Such scenarios have the ability to capture the diminishing returns of restoration in conditions of extreme stress by the addition of environmental stress dynamics to such scenarios, giving a more subtle judgment of policy performance.

The time aspect of land system management is also emphasized by scenario-based optimization. Short-term optimization can afford more of the losses of carbon to carry on with economic development, whereas long-term optimization gives preference to land use, which stabilizes or even increases the storage of carbon with time. The trade-off is especially applicable to areas in the mining industry that are in a transition to post-mining development [53].

5.4. Trade-Offs and Synergies among Mining, the Environment, and Carbon Objectives

The coordinated optimization indicates the existence of trade-offs and synergies between mining activities on the one hand and environmental protection on the other, and carbon storage. The most apparent trade-offs are those in which mining expansion occurs at the direct expense of high-carbon land or where mining exerts stress on the environment to the point of being beyond the recoverable levels. Even optimal land use structures, even in these situations, might not contain losses of carbon, which highlights the constraints of technical responses in the absence of structural transformations in resource utilization [54,55].

Simultaneously, synergies may also arise when land recovery and ecological restoration are planned in accordance with carbon goals. Reclaimed mining areas, with the right vegetation planted on them, can be carbon-sequestration capable in a slower and gradual way, and gradually gain the capacity, as well as decrease erosion and enhance the connectivity of the landscapes. Frameworks of optimization that take into consideration the stress on the environment can be used to determine the most likely locations of such synergies, and not to invest in a region where conditions are extremely averse to the success of restoration. Realistic land use planning requires that these trade-offs and synergies be understood. Coordinated optimization focuses on regional context-specific strategies based on the priorities of environmental capacity and development, instead of the global optimization of the final results. **Table 4** summarizes the main elements and purposes of coordinated land use and carbon storage optimization systems in the mining areas [56].

Table 4. Core components, objectives, and expected outcomes of coordinated optimization frameworks for land use and carbon storage in mining regions.

Optimization Component	Typical Indicators	Role of Environmental Stress	Expected Optimization Outcome
Land use demand	Mining land, construction land area	Stress limits land suitability	Spatially concentrated mining
Carbon storage objective	Total ecosystem carbon	Stress reduces sequestration efficiency	Protection of high-carbon land
Ecological constraints	Erosion, water stress indices	Hard constraints or penalties	Avoidance of highly stressed zones
Scenario settings	Development and restoration pathways	Stress evolution differs by scenario	Policy-relevant land use patterns

5.5. Implications for Sustainable Land Use Planning and Policy

There are significant implications for land use planning and environmental regulation in mining areas regarding the application of coordinated optimization frameworks. These methods present quantitative evidence to support policy-making concerning the balance between economic progress and responsibility to the environment by explicitly relating land use choices to carbon storage performance and environmental limitations. They also provide a way of assessing the possible capacity of land management to contribute to wider climate mitigation objectives.

In the case of, e.g., parts of Shaanxi in the north, where mining is still one of the pillars of the regional economy, coordinated optimization can also be used to inform spatial zoning, reclamation priorities, and the design of restoration policy. Notably, these frameworks help to change a reactive mitigation approach to proactive planning so that decision-makers can predict future effects of land use decisions in the face of environmental stress. Coordinated optimization, therefore, is an important interface between land system science and sustainable development practice in mining-affected landscapes [57–60]. An integrated framework combining environmental stress simulation, land use evolution modeling, carbon storage assessment, and coordinated optimization is presented in **Figure 2**.

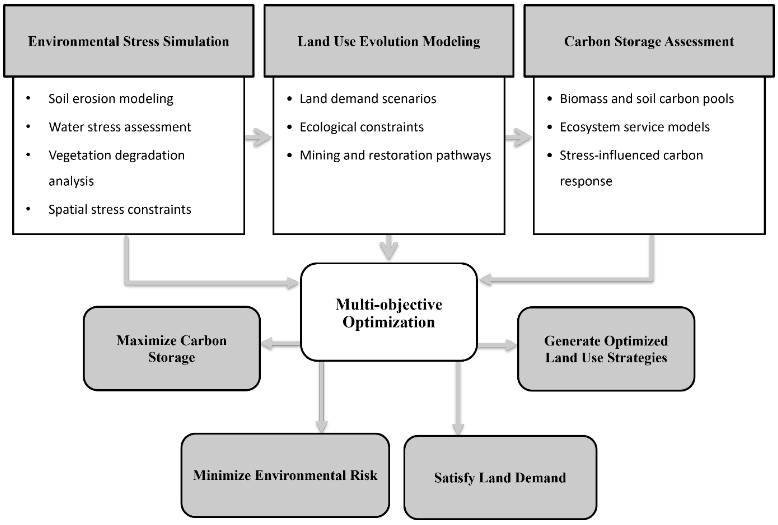

Figure 2. Integrated framework for coordinated optimization of land use and carbon storage under environmental constraints in mining regions.

6. Conclusions

This review highlights that mining-driven land use evolution in the Shaanxi Northern Mining Area Basin is fundamentally governed by the dynamic interplay between environmental stress processes, land system transitions, and carbon storage responses. A central insight emerging from this synthesis is the necessity of moving beyond loosely coupled or sequential approaches toward fully integrated stress–carbon–land modeling frameworks capable of capturing feedbacks among ecological degradation, land use decisions, and carbon dynamics under mining disturbance.

Despite notable progress, several methodological gaps remain. First, uncertainty propagation across model components, from environmental stress quantification to land use simulation and carbon estimation, remains insufficiently addressed, limiting the robustness of scenario-based decision support. Second, current models often lack a realistic representation of multi-scale interactions, particularly the mismatch between ecological processes and administrative or planning units. Third, the role of socio-economic drivers and policy interventions is frequently simplified, constraining the ability to simulate adaptive land use pathways under evolving governance and market conditions.

Looking forward, future research should prioritize the development of coupled, multi-scale modeling systems that explicitly integrate environmental stress dynamics, land use transitions, and carbon processes. Particular attention is needed to improve uncertainty quantification, enhance data assimilation using long-term monitoring and remote sensing, and incorporate behaviorally informed socio-economic modules. In addition, critical unresolved questions include how to balance mining development with ecological restoration under water-limited conditions, how restoration trajectories influence long-term carbon sequestration, and how policy instruments can effectively coordinate land use and carbon objectives.

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The author declares no conflict of interest.

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The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Mashala, M.J., Dube, T., Mudereri, B.T., et al., 2023. A Systematic Review on Advancements in Remote Sensing for Assessing and Monitoring Land Use and Land Cover Changes Impacts on Surface Water Resources in Semi-Arid Tropical Environments. Remote Sensing. 15(16), 3926. DOI: https://doi.org/10.3390/rs15163926

[2] Han, J., Hu, Z., Mao, Z., et al., 2022. How to Account for Changes in Carbon Storage from Coal Mining and Reclamation in Eastern China? Taking Yanzhou Coalfield as an Example to Simulate and Estimate. Remote Sensing. 14(9), 2014. DOI: https://doi.org/10.3390/rs14092014

[3] Zhu, X., Li, J., Cheng, H., et al., 2022. Assessing the impacts of ecological governance on carbon storage in an urban coal mining subsidence area. Ecological Informatics. 72, 101901. DOI: https://doi.org/10.1016/j.ecoinf.2022.101901

[4] Yang, Z., Li, W., Pei, Y., et al., 2018. Classification of the type of eco-geological environment of a coal mine district: A case study of an ecologically fragile region in Western China. Journal of Cleaner Production. 174, 1513–1526. DOI: https://doi.org/10.1016/j.jclepro.2017.11.049

[5] Wang, N., Luo, Y., Liu, Z., et al., 2022. Spatial distribution characteristics and evaluation of soil pollution in coal mine areas in Loess Plateau of northern Shaanxi. Scientific Reports. 12(1), 16440. DOI: https://doi.org/10.1038/s41598-022-20865-6

[6] Li, W., Liu, S., Pei, Y., et al., 2018. Zoning for eco-geological environment before mining in Yushenfu mining area, northern Shaanxi, China. Environmental Monitoring and Assessment. 190(10), 619. DOI: https://doi.org/10.1007/s10661-018-6996-5

[7] Lian, X., Hu, H., Li, T., et al., 2020. Main geological and mining factors affecting ground cracks induced by underground coal mining in Shanxi Province, China. International Journal of Coal Science & Technology. 7(2), 362–370. DOI: https://doi.org/10.1007/s40789-020-00308-1

[8] Zhang, K., Liu, S., Bai, L., et al., 2023. Effects of Underground Mining on Soil–Vegetation System: A Case Study of Different Subsidence Areas. Ecosystem Health and Sustainability. 9, 0122. DOI: https://doi.org/10.34133/ehs.0122

[9] Singh, H., Shah, S., Giri, K., et al., 2026. Carbon Neutrality and Environmental Sustainability: Concept and Significance. In: Singh, H. (Ed.). Forestry for a Carbon-Neutral and Sustainable Future, Sustainability Solutions. Springer Nature: Cham, Switzerland. pp. 1–25. DOI: https://doi.org/10.1007/978-3-032-06427-1_1

[10] Liu, K., Cheng, P., Zhang, A., et al., 2025. Beyond environmental sustainability: Low-carbon land use policies can contribute to the realization of comprehensive sustainable development. Sustainable Development. 33(1), 1315–1332. DOI: https://doi.org/10.1002/sd.3180

[11] Wang, G., Zhou, J., 2025. Optimizing the spatial layout of mining areas to help carbon neutrality: Land use change driven by improved NSGA II algorithms. Environment, Development and Sustainability. DOI: https://doi.org/10.1007/s10668-025-06255-8

[12] Ma, J., Zhou, Y., He, L., 2025. A Systematic Review of Carbon Sink Pathways and Deployment Strategies. Preprints. DOI: https://doi.org/10.20944/preprints202509.0346.v1

[13] Li, S., Dan, Z., Yin, T., 2026. Mining-induced land use change and ecological restoration: Lessons from three developing economies. Physics and Chemistry of the Earth, Parts A/B/C. 142, 104267. DOI: https://doi.org/10.1016/j.pce.2025.104267

[14] Padhiary, M., Kumar, R., 2024. Assessing the Environmental Impacts of Agriculture, Industrial Operations, and Mining on Agro-Ecosystems. In: Azrour, M., Mabrouki, J., Alabdulatif, A., et al. (Eds.). Smart Internet of Things for Environment and Healthcare, Studies in Computational Intelligence. Springer Nature: Cham, Switzerland. pp. 107–126. DOI: https://doi.org/10.1007/978-3-031-70102-3_8

[15] Song, W., Song, W., Gu, H., et al., 2020. Progress in the Remote Sensing Monitoring of the Ecological Environment in Mining Areas. International Journal of Environmental Research and Public Health. 17(6), 1846. DOI: https://doi.org/10.3390/ijerph17061846

[16] Dhakate, R., Modi, D., Rao, V.V.S.G., 2019. Impact assessment of coal mining on river water and groundwater and its interaction through hydrological, isotopic characteristics, and simulation flow modeling. Arabian Journal of Geosciences. 12(1), 8. DOI: https://doi.org/10.1007/s12517-018-4110-5

[17] Smith, P., House, J.I., Bustamante, M., et al., 2016. Global change pressures on soils from land use and management. Global Change Biology. 22(3),

1008–1028. DOI: https://doi.org/10.1111/gcb.13068

[18] Ekka, P., Patra, S., Upreti, M., et al., 2023. Land Degradation and Its Impacts on Biodiversity and Ecosystem Services. In: Raj, A., Jhariya, M.K., Banerjee, A., et al. (Eds.). Land and Environmental Management through Forestry. Wiley: London, UK. pp. 77–101. DOI: https://doi.org/10.1002/9781119910527.ch4

[19] Punia, A., Bharti, R., 2023. Loss of soil organic matter in the mining landscape and its implication to climate change. Arabian Journal of Geosciences. 16(1), 86. DOI: https://doi.org/10.1007/s12517-023-11177-8

[20] Paraskevis, N., Servou, A., Roumpos, C., et al., 2021. Spatiotemporal Interactions between Surface Coal Mining and Land Cover and Use Changes. Journal of Sustainable Mining. 20(2), 72–89. DOI: https://doi.org/10.46873/2300-3960.1053

[21] Su, Y., Ma, X., Feng, Q., et al., 2023. Patterns and controls of ecosystem service values under different land-use change scenarios in a mining-dominated basin of northern China. Ecological Indicators. 151, 110321. DOI: https://doi.org/10.1016/j.ecolind.2023.110321

[22] Song, J., Yang, Z., Xia, J., et al., 2021. The impact of mining-related human activities on runoff in northern Shaanxi, China. Journal of Hydrology. 598, 126235. DOI: https://doi.org/10.1016/j.jhydrol.2021.126235

[23] Lambin, E.F., Meyfroidt, P., 2010. Land use transitions: Socio-ecological feedback versus socio-economic change. Land Use Policy. 27(2), 108–118. DOI: https://doi.org/10.1016/j.landusepol.2009.09.003

[24] Kerényi, A., McIntosh, R.W., 2020. Changes on Earth as a Result of Interaction Between the Society and Nature. In Sustainable Development in Changing Complex Earth Systems, Sustainable Development Goals Series. Springer International Publishing: Cham, Switzerland. pp. 75–202. DOI: https://doi.org/10.1007/978-3-030-21645-0_4

[25] Patel, J.B., Raval, Z., 2024. The Impacts of Urbanization on Ecological Systems: A Comprehensive Study of the Complex Challenges Arising from Rapid Urban Growth. Research Review Journal of Indian Knowledge Systems. 1(1), 1–10. DOI: https://doi.org/10.31305/rrjiks.2024.v1.n1.001

[26] Zine, H., Hakkou, R., Papazoglou, E.G., et al., 2024. Revegetation and ecosystem reclamation of post-mined land: toward sustainable mining. International Journal of Environmental Science and Technology. 21(15), 9775–9798. DOI: https://doi.org/10.1007/s13762-024-05697-3

[27] Noszczyk, T., 2019. A review of approaches to land use changes modeling. Human and Ecological Risk Assessment: An International Journal. 25(6), 1377–1405. DOI: https://doi.org/10.1080/10807039.2018.1468994

[28] Firozjaei, M.K., Sedighi, A., Firozjaei, H.K., et al., 2021. A historical and future impact assessment of mining activities on surface biophysical characteristics change: A remote sensing-based approach. Ecological Indicators. 122, 107264. DOI: https://doi.org/10.1016/j.ecolind.2020.107264

[29] Aspinall, R., Staiano, M., 2017. A Conceptual Model for Land System Dynamics as a Coupled Human–Environment System. Land. 6(4), 81. DOI: https://doi.org/10.3390/land6040081

[30] Mia, M., Karikar, B.A., Mohibul, S., et al., 2026. Environmental and Socio-economic Impacts of River Sand and Gravel Mining: A Review. Environmental Management. 76(3), 76. DOI: https://doi.org/10.1007/s00267-025-02370-4

[31] Blanco, H., Lal, R., 2023. Soil Resilience. In Soil Conservation and Management. Springer Nature: Cham, Switzerland. pp. 525–544. DOI: https://doi.org/10.1007/978-3-031-30341-8_21

[32] Chang, X., Zhang, F., Cong, K., et al., 2021. Scenario simulation of land use and land cover change in mining area. Scientific Reports. 11(1), 12910. DOI: https://doi.org/10.1038/s41598-021-92299-5

[33] Lucas, L.V., Brown, C.J., Robertson, D.M., et al., 2025. Gaps in Water Quality Modeling of Hydrologic Systems. Water. 17(8), 1200. DOI: https://doi.org/10.3390/w17081200

[34] Sonter, L.J., Moran, C.J., Barrett, D.J., et al., 2014. Processes of land use change in mining regions. Journal of Cleaner Production. 84, 494–501. DOI: https://doi.org/10.1016/j.jclepro.2014.03.084

[35] Magris, R.A., Marta-Almeida, M., Monteiro, J.A.F., et al., 2019. A modelling approach to assess the impact of land mining on marine biodiversity: Assessment in coastal catchments experiencing catastrophic events (SW Brazil). Science of The Total Environment. 659, 828–840. DOI: https://doi.org/10.1016/j.scitotenv.2018.12.238

[36] Azimi Sardari, M.R., Bazrafshan, O., Panagopoulos, T., et al., 2019. Modeling the Impact of Climate Change and Land Use Change Scenarios on Soil Erosion at the Minab Dam Watershed. Sustainability. 11(12), 3353. DOI: https://doi.org/10.3390/su11123353

[37] Feng, Y., Harrison, J.P., Bozorgzadeh, N., 2019. Uncertainty in In Situ Stress Estimations: A Statistical Simulation to Study the Effect of Numbers of Stress Measurements. Rock Mechanics and Rock Engineering. 52(12), 5071–5084. DOI: https://doi.org/10.1007/s00603-019-01891-9

[38] Li, G., Mizuta, Y., Ishida, T., et al., 2009. Stress field determination from local stress measurements by numerical modelling. International Journal of Rock Mechanics and Mining Sciences. 46(1), 138–147. DOI: https://doi.org/10.1016/j.ijrmms.2008.07.009

[39] Yu, H., Zahidi, I., 2023. Environmental hazards posed by mine dust, and monitoring method of mine dust pollution using remote sensing technologies: An overview. Science of The Total Environment. 864, 161135. DOI:

https://doi.org/10.1016/j.scitotenv.2022.161135

[40] Hu, B., Zhang, Q., Li, S., et al., 2022. Application of Numerical Simulation Methods in Solving Complex Mining Engineering Problems in Dingxi Mine, China. Minerals. 12(2), 123. DOI: https://doi.org/10.3390/min12020123

[41] Bastante, F.G., Taboada, J., Alejano, L., et al., 2008. Optimization tools and simulation methods for designing and evaluating a mining operation. Stochastic Environmental Research and Risk Assessment. 22(6), 727–735. DOI: https://doi.org/10.1007/s00477-007-0182-6

[42] Feng, H., Wang, S., Zou, B., et al., 2023. Contribution of land use and cover change (LUCC) to the global terrestrial carbon uptake. Science of The Total Environment. 901, 165932. DOI: https://doi.org/10.1016/j.scitotenv.2023.165932

[43] Gomes, L.C., Faria, R.M., De Souza, E., et al., 2019. Modelling and mapping soil organic carbon stocks in Brazil. Geoderma. 340, 337–350. DOI: https://doi.org/10.1016/j.geoderma.2019.01.007

[44] Estes, L., Chen, P., Debats, S., et al., 2018. A large-area, spatially continuous assessment of land cover map error and its impact on downstream analyses. Global Change Biology. 24(1), 322–337. DOI: https://doi.org/10.1111/gcb.13904

[45] Ren, H., Zhao, Y., He, T., 2025. Remote Sensing in Mining-Related Eco-Environmental Monitoring and Assessment. Remote Sensing. 18(1), 103. DOI: https://doi.org/10.3390/rs18010103

[46] Lu, C., Wang, K., 2023. Natural resource conservation outpaces and climate change: Roles of reforestation, mineral extraction, and natural resources depletion. Resources Policy. 86, 104159. DOI: https://doi.org/10.1016/j.resourpol.2023.104159

[47] Tang, N., 2025. Barriers, Opportunities, and Pathways for Climate Adaptation in China Toward Carbon Neutrality: Sustainable Mining Practices and Land Management. Land Degradation & Development. 36(18), 6564–6581. DOI: https://doi.org/10.1002/ldr.70091

[48] Guo, H., Yu, Q., Pei, Y., et al., 2021. Optimization of landscape spatial structure aiming at achieving carbon neutrality in desert and mining areas. Journal of Cleaner Production. 322, 129156. DOI: https://doi.org/10.1016/j.jclepro.2021.129156

[49] Simpson, G.B., Ferguson, K., Slingerland, N., et al., 2025. Integrating the sustainable development goals into post-mining land use selection. Scientific Reports. 15(1), 31974. DOI: https://doi.org/10.1038/s41598-025-15980-z

[50] Zhou, D., Xu, J., Lin, Z., 2017. Conflict or coordination? Assessing land use multi-functionalization using production-living-ecology analysis. Science of The Total Environment. 577, 136–147. DOI: https://doi.org/10.1016/j.scitotenv.2016.10.143

[51] Li, X., Lu, Z., 2025. Exploring the Balance Between Ecosystem Services and Economic Benefits via Multi-Objective Land Use Optimization. Land. 14(5), 920. DOI: https://doi.org/10.3390/land14050920

[52] Liu, Y., Guo, H., Zhang, Z., et al., 2007. An Optimization Method Based on Scenario Analysis for Watershed Management Under Uncertainty. Environmental Management. 39(5), 678–690. DOI: https://doi.org/10.1007/s00267-006-0029-9

[53] Fan, Y., Wang, L., Song, Y., 2025. Ecological Effect Assessment and Reclamation Pattern of Surface Mining: Based on the Perspective of Ecosystem Services. International Journal of Environmental Research. 19(5), 198. DOI: https://doi.org/10.1007/s41742-025-00854-z

[54] Zhang, Y., Zhao, D., Hou, H., et al., 2022. Change in Landscape Multifunctionality and Its Trade-off–Synergy Relationship in Mined Land. Land. 11(11), 1948. DOI: https://doi.org/10.3390/land11111948

[55] Renaud, F.G., Zhou, X., Bosher, L., et al., 2022. Synergies and trade-offs between sustainable development goals and targets: innovative approaches and new perspectives. Sustainability Science. 17(4), 1317–1322. DOI: https://doi.org/10.1007/s11625-022-01209-9

[56] Dong, J., Guo, Z., Zhao, Y., et al., 2023. Coupling coordination analysis of industrial mining land, landscape pattern and carbon storage in a mining city: A case study of Ordos, China. Geomatics, Natural Hazards and Risk. 14(1), 2275539. DOI: https://doi.org/10.1080/19475705.2023.2275539

[57] Zhang, J., Fu, M., Hassani, F.P., et al., 2011. Land Use-Based Landscape Planning and Restoration in Mine Closure Areas. Environmental Management. 47(5), 739–750. DOI: https://doi.org/10.1007/s00267-011-9638-z

[58] Guo, W., Teng, Y., Yan, Y., et al., 2022. Simulation of Land Use and Carbon Storage Evolution in Multi-Scenario: A Case Study in Beijing-Tianjin-Hebei Urban Agglomeration, China. Sustainability. 14(20), 13436. DOI: https://doi.org/10.3390/su142013436

[59] Chen, G., Peng, Q., Fan, Q., et al., 2024. Spatial-Temporal Variation and Driving Forces of Carbon Storage at the County Scale in China Based on a Gray Multi-Objective Optimization-Patch-Level Land Use Simulation-Integrated Valuation of Ecosystem Services and Tradeoffs-Optimal Parameter-Based Geographical Detector Model: Taking the Daiyun Mountain's Rim as an Example. Land. 14(1), 14. DOI: https://doi.org/10.3390/land14010014

[60] Tan, L., Zhang, Z., Luo, W., et al., 2026. Terrestrial ecosystem carbon storage responses to land cover evolution under future multi-scenario in ecological function zone for soil and water conservation of the Three Gorges Reservoir, China. Geocarto International. 41(1), 2621457. DOI: https://doi.org/10.1080/10106049.2026.2621457