

Ecological Recovery of Karst Ecosystems under Rocky Desertification

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Abstract: Karst rocky desertification is a major form of ecological degradation caused by the interaction of natural geological conditions and human activities. Shallow soils, high water loss, and strong habitat heterogeneity make ecological restoration in karst areas challenging. Although vegetation restoration, soil and water conservation, and forest and grassland restoration have improved ecological conditions in many areas, traditional approaches often focus on increasing vegetation cover and may overlook differences in degradation levels and ecosystem functions. Based on a review of existing studies, this paper examines the main mechanisms of ecological restoration, including vegetation–soil interactions, water regulation, community structure, and microhabitat effects. It further compares restoration strategies under different levels of rocky desertification. The review suggests that effective restoration should move from vegetation recovery alone toward the coordinated restoration of vegetation, soil, water, and habitat conditions. Restoration strategies should also be adapted to local degradation levels. Mild and moderate areas should focus on plant community improvement and soil restoration, while severe areas should give greater attention to microhabitat improvement and stress-tolerant pioneer species. Based on these findings, an integrated framework linking rocky desertification level, habitat characteristics, plant selection, and restoration measures is proposed to support targeted management and long-term ecosystem recovery in karst areas.

Keywords: Karst Rocky Desertification; Ecological Restoration; Sustainable Development; Sustainable Management

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1. Introduction

Karst landscapes are widely distributed in many parts of the world, and southwestern China is one of the major karst regions globally (Qin et al., 2022). Guizhou, Guangxi, and Yunnan have extensive areas of carbonate rocks, which have formed complex landscapes such as mountains, peak-cluster depressions, depressions, and gorges. Karst areas are characterized by well-developed karst features, shallow soils, discontinuous soil layers, and distinctive hydrological processes. These conditions make karst ecosystems highly sensitive to human disturbance (Zhu et al., 2026).

The concept of rocky desertification was introduced in the 1990s, but there is still no fully unified definition in academic literature (Guo et al., 2022). In China, rocky desertification is commonly described as a process in which vegetation degradation, soil erosion, reduced soil cover, and extensive bedrock exposure occur under human disturbance in karst areas (Bai et al., 2025). Therefore, rocky desertification is not simply a reduction in vegetation. It results from changes in vegetation, soil, hydrological processes, and landform conditions.

China has implemented a range of measures to control rocky desertification, including forest protection, returning farmland to forest and grassland, soil and water conservation, ecological agriculture, and the use of alternative energy sources. These measures have improved vegetation cover and reduced soil erosion in many areas (Lv et al., 2025). However, some areas still rely mainly on single-species economic forests or monoculture plantations, which can lead to simple plant community structures. Similar restoration approaches are also sometimes applied to areas with different levels of rocky desertification. These problems show that current management needs to move beyond simply increasing vegetation cover and place greater emphasis on restoring ecosystem structure and functions.

Based on a review of relevant studies from China and other countries, this paper focuses on three questions: (1) What are the main mechanisms of ecological restoration in karst rocky desertification areas? (2) What differentiated restoration strategies should be used for different levels of rocky desertification? (3) How can plant selection and arrangement, soil restoration, and microhabitat management be integrated into a comprehensive restoration framework?

2. Formation of Rocky Desertification and Characteristics of Ecological Degradation

The widespread distribution of carbonate rocks, well-developed karst fissures, shallow soils, and fragmented terrain make karst ecosystems highly sensitive to environmental changes (Lv et al., 2025). Under these conditions, inappropriate land use, vegetation destruction, and resource exploitation can further increase soil erosion and vegetation degradation, thereby promoting the development of rocky desertification (Zhang et al., 2023).

2.1 Natural Factors

Carbonate rocks are easily dissolved by water. The development of rock fissures and underground karst channels leads to a highly uneven distribution of surface soils. As a result, soils are often shallow and discontinuous. At the same time, many areas in southwestern China have steep slopes. Complex landforms, including peak clusters, depressions, and valleys, increase the risks of surface runoff and soil erosion (Wang et al., 2021).

Southwestern China receives relatively high amounts of rainfall, but rainfall is unevenly distributed across seasons. Heavy rainfall during the wet season can generate strong surface runoff and increase the loss of soil and nutrients. At the same time, well-developed karst fissures allow part of the rainfall to infiltrate rapidly into the ground. This can reduce the amount of water available to plants. The combined effects of concentrated rainfall, increased runoff, soil loss, rapid infiltration, and low soil water availability can therefore limit vegetation establishment and recovery. Therefore, geological conditions, complex terrain, seasonal rainfall, and shallow soils together increase the vulnerability of karst ecosystems and provide the basic environmental conditions for the development of rocky desertification.

2.2 Human Factors

A fragile natural environment does not necessarily lead to rocky desertification. Its further development is closely related to human activities. In karst areas, available farmland is relatively limited, so some agricultural activities are carried out on slopes, in depressions, and in areas around exposed rocks and fissures (Zhao et al., 2022). Inappropriate farming practices can damage surface vegetation and soil structure, which increases rainfall erosion and soil loss. Forest logging, land clearing, and fuelwood collection can also reduce vegetation cover. These activities weaken the ability of plant roots to stabilize soil and vegetation canopies to reduce rainfall impact, further reducing soil and water conservation capacity (Hussein, 2023).

In addition, mining, road construction, and other engineering activities can disturb the local land surface and increase soil loss and vegetation damage (Arif et al., 2024). In some areas with relatively low levels of economic development, long-term pressure on land and forest resources may further increase ecological degradation (Zhang et al., 2024). Therefore, rocky desertification is not determined by natural conditions alone. It results from the combined effects of environmental vulnerability and human disturbance.

2.3 Characteristics of Ecological Degradation

As rocky desertification becomes more severe, ecosystems generally show continuous changes in vegetation, soil quality, and water retention. Vegetation loss reduces canopy interception and root-based soil stabilization, which can increase surface runoff and soil erosion (Liu et al., 2024). Soil erosion then reduces soil depth and the contents of organic matter and nutrients, which limits plant growth and natural regeneration (Zhao et al., 2026). This creates a negative feedback process in which

vegetation degradation increases soil loss, while the decline in soil and water and nutrient retention further limits vegetation recovery.

As this process continues, plant species richness and community structural complexity gradually decrease. Ecosystem stability and recovery capacity also decline (Zhang et al., 2022). Therefore, different levels of rocky desertification reflect different degrees of vegetation, soil, and habitat degradation. They also involve different limiting factors and require different levels of restoration intervention.

3. Research Progress in Ecological Restoration of Rocky Desertification

As research on rocky desertification management has developed, the focus of ecological restoration has gradually shifted from identifying the causes of rocky desertification and increasing vegetation cover to the recovery of plant community structure, soil quality, biodiversity, and ecosystem functions (He et al., 2023; Quoreshi et al., 2022). Existing studies show that ecological restoration in rocky desertification areas is not simply a process of increasing vegetation cover. It involves interactions among vegetation, soil, water, and habitat conditions (Park et al., 2024; Lv et al., 2025). In recent years, research has mainly focused on vegetation community reconstruction, soil quality improvement, and the effects of habitat heterogeneity on ecological recovery. This work shows a gradual shift from single restoration measures toward integrated ecosystem restoration (Lu et al., 2026).

3.1 Vegetation Restoration and Community Structure Reconstruction

Vegetation restoration is one of the most widely used measures for controlling rocky desertification. It helps reduce exposed land, control soil erosion, and promote ecosystem recovery. Early restoration practices mainly included forest protection, returning farmland to forest and grassland, and artificial afforestation. These measures aimed to improve degraded environments by increasing vegetation cover.

As research has developed, restoration approaches that focus only on vegetation cover have received increasing attention. Studies have shown that plant species composition and community structure also affect ecosystem stability and recovery. Single-species plantations or monoculture forests can increase vegetation cover in the short term, but they may not form stable and structurally diverse plant communities (Sadia et al., 2024). Therefore, recent studies have placed more emphasis on the appropriate combination of trees, shrubs, and herbs, as well as the selection of native and functional plant species (Chen et al., 2025). Different plant species have different functions in root distribution, drought tolerance, nutrient use, and soil and water conservation. Combining multiple species can provide functional complementarity and improve community stability (Xue et al., 2026). At the same time, fruit forests and other ecological and economic plants remain useful where ecological restoration needs to support local economic development. However, their use should avoid excessive dependence on a single economic species (Cosmulescu et al., 2026).

3.2 Coordinated Restoration of Soil and Vegetation

Soil degradation is an important factor limiting vegetation recovery in karst areas. As rocky desertification becomes more severe, soil depth, organic matter, nutrient content, and water-holding capacity generally decrease. These changes limit plant growth and community regeneration (Li et al., 2022). Therefore, ecological restoration has gradually shifted from vegetation recovery alone toward coordinated restoration of vegetation and soil.

Studies have shown that vegetation recovery can improve soil structure through root growth, litter accumulation, and organic matter input. It can also increase soil nutrient and water retention (Wang et al., 2023; Xu et al., 2026). At the same time, improved soil conditions promote plant establishment and growth, creating positive feedback between vegetation and soil (Zhu et al., 2022; Wang et al., 2025). This process shows that rocky desertification management should address both vegetation recovery and soil quality improvement. In areas with moderate or more severe rocky desertification, appropriate soil and water conservation and soil improvement measures should be selected according to the main soil limitations.

3.3 Habitat Heterogeneity and Ecological Restoration

Karst areas have fragmented terrain and uneven soil distribution. Water and nutrient conditions can therefore differ greatly among different slope positions, depressions, valleys, and rock fissures. As a result, restoration success depends not only on plant species but also on local habitat conditions.

The role of microhabitats in ecological restoration has received increasing attention. Some rock fissures, depressions, and valleys can accumulate soil, water, and essential nutrients. These areas can provide more suitable conditions for plant establishment (Dang et al., 2026). Habitat heterogeneity is especially important in areas with severe and very severe rocky desertification because soil resources are limited in these areas. Large-scale and uniform restoration can therefore face strong environmental constraints. Targeted restoration based on suitable microhabitats may help plants establish first and then gradually expand the restored area through community development and succession. This approach may be particularly useful for ecological restoration in highly degraded areas (Borges Neto et al., 2025).

In addition, the potential roles of mosses and biological soil crusts as pioneer organisms in harsh environments deserve further attention. Mosses can tolerate difficult environmental conditions and can retain water, accumulate organic matter, and improve local microhabitats. They may therefore play an important role during the early stages of ecological restoration in severely degraded areas (Fendane et al., 2025). This suggests that ecological restoration of rocky desertification should consider the functions of different biological groups at different stages of community succession, rather than focusing mainly on trees and shrubs.

4. Mechanisms of Ecological Restoration in Karst Rocky Desertification Areas

Ecological restoration of rocky karst desertification is a gradual process in which vegetation, soil, water, and habitat conditions interact with each other. Because karst areas often have shallow soils, low water-holding capacity, and high habitat heterogeneity, simply increasing vegetation cover cannot always maintain long-term restoration. Existing studies show that vegetation recovery can improve soil and water conditions, while better soil and habitat conditions can further promote plant establishment and community succession (Li et al., 2023). Therefore, a key goal of ecological restoration is to restore positive feedback among these ecological components.

4.1 Vegetation–Soil Feedback

Soil degradation is an important factor limiting vegetation recovery in rocky desertification areas. As rocky desertification becomes more severe, soil depth, organic matter, nutrient content, and water-holding capacity generally decrease. These changes limit plant growth and community regeneration (Zheng et al., 2024; Zheng et al., 2023). At the same time, vegetation recovery can improve soil structure through root growth, litter accumulation, and organic matter input. It can also reduce soil erosion and promote nutrient accumulation (Wu et al., 2024).

Improved soil conditions can increase plant access to water and nutrients and promote plant establishment and growth. This can further increase vegetation cover. In this way, vegetation and soil form a positive feedback process: vegetation recovery improves soil quality and water and nutrient availability, which promotes plant growth and further vegetation recovery. This feedback shows that vegetation restoration and soil restoration should not be treated as separate processes. In areas with moderate or more severe rocky desertification, plant selection and arrangement should be combined with soil and water conservation and soil improvement measures according to limitations such as soil depth, organic matter, and water availability.

4.2 Water Regulation

Water is an important limiting factor for ecological restoration in karst areas. Although southwestern China receives relatively high amounts of rainfall, well-developed karst fissures allow part of the rainfall to infiltrate rapidly. At the same time, concentrated rainfall can produce strong surface runoffs and cause rapid loss of water and soil resources. Therefore, improving the effective use of rainfall is an important part of rocky desertification restoration.

Vegetation can reduce surface runoff through canopy interception, litter cover, and root-based soil stabilization. These processes can also increase the time that water remains in the soil (Xin et al., 2025). Different plant types may also use water in different ways. Trees, shrubs, and herbs have different root depths and spatial distributions, which can help improve the use of limited soil water resources (Jiang et al., 2023).

Therefore, ecological restoration should not focus only on increasing vegetation cover. It should also consider the role of vegetation in water retention and water use. In areas with strong water limitations, drought-tolerant and nutrient-tolerant

native plants should be given priority. Plant selection and arrangement should also consider local terrain and microhabitat conditions.

4.3 Community Structure and Biodiversity

As soil and water conditions deteriorate, vegetation may gradually change from relatively complex tree–shrub–herb communities to shrub–herb or single-herb communities. Community stability and ecological functions may also decline (Zhu et al., 2026). Therefore, ecological restoration should focus not only on plant abundance and vegetation cover but also on the recovery of community structure and species diversity.

Trees, shrubs, and herbs have different functions in canopy interception, root-based soil stabilization, water use, and nutrient cycling. A multi-layered and multi-species plant community can provide functional complementarity and improve community structure and ecosystem stability (Xin et al., 2025). Compared with single-species plantations or monoculture forests, appropriate combinations of trees, shrubs, and herbs are more likely to form stable community structures.

However, plant selection and arrangement should still be adjusted according to the degree of rocky desertification. In mildly degraded areas, mixed planting and natural succession can be strengthened. In moderately degraded areas, stress-tolerant plants can be combined with suitable economic plants. In severely degraded areas, priority should be given to establishing pioneer and drought-tolerant plants.

4.4 Microhabitats and Community Succession

Karst areas have fragmented terrain. Rock fissures, depressions, valleys, and lower slopes form different types of microhabitats, with clear differences in soil, water, and nutrient conditions. Some microhabitats can accumulate soil and organic matter and provide relatively suitable conditions for plant establishment (Wang et al., 2022). Microhabitats in southwestern China can also provide suitable conditions for the growth of some economic plants and can support both ecological restoration and local economic use (Dang et al., 2026). This shows that microhabitats can serve as important spatial units for plant establishment and community recovery in rocky desertification areas.

In areas with severe and very severe rocky desertification, large-scale uniform afforestation is strongly limited by the lack of soil and water. Therefore, suitable microhabitats such as rock fissures, depressions, and valleys can be used first for localized restoration. Pioneer plants can be established in these areas to gradually improve local soil and water conditions. This can then support the establishment of other plant species and promote community succession. The process can be summarized as: microhabitat improvement→ pioneer plant establishment→ improvement of soil and water conditions→ plant expansion→ community recovery. This gradual expansion from suitable microhabitats to surrounding areas is more consistent with the fragmented habitats and uneven distribution of resources in karst landscapes.

4.5 Integrated Restoration Mechanisms and Gradient-Based Restoration

Ecological restoration of karst rocky desertification is not a single vegetation recovery process. It is a coordinated process involving vegetation, soil, water, and habitat conditions. Vegetation recovery increases surface cover and reduces soil erosion. Root growth can also improve soil structure and water retention. Improved soil and water conditions then provide better conditions for plant growth and community recovery. As vegetation gradually recovers, community structure and species composition can improve, which further strengthens soil and water conservation, resource use, and environmental regulation. At the same time, microhabitats such as rock fissures, depressions, and valleys can provide relatively suitable soil and water conditions for plant establishment. They are especially important as an ecological base for restoration in areas with severe and very severe rocky desertification. These processes form positive feedback in which vegetation recovery, soil improvement, water retention, community reconstruction, and habitat improvement promote each other.

Therefore, the basic approach to rocky desertification restoration should shift from single vegetation restoration to coordinated restoration of vegetation, soil, water, and habitat conditions. Since the main ecological limitations and natural recovery capacity differ among levels of rocky desertification, restoration measures should also match the degree of degradation. A gradient-based restoration approach can therefore be developed, ranging from natural recovery to assisted restoration and then to target microhabitat restoration.

Table 1: Ecological Restoration Strategies for Different Levels of Rocky Desertification

Level of rocky desertification	Main characteristics	Plant selection and arrangement	Main restoration approach
Potential	Vegetation is relatively intact and soil conditions are relatively good	Native trees and shrubs	Forest protection and natural recovery
Mild	Reduced vegetation cover and mild soil erosion	Mixed trees, shrubs, and herbs	Forest protection, mixed planting, and soil and water conservation
Moderate	Reduced soil depth and nutrient availability	Shrubs, herbs, and suitable trees	Coordinated vegetation restoration and soil improvement
Severe	Extensively exposed rock and fragmented habitats	Drought-tolerant shrubs, herbs, and pioneer plants	Microhabitat restoration and assisted planting
Very severe	Large areas of exposed rock and very limited soil	Mosses, biological soil crusts, and pioneer plants	Microenvironment improvement, biological soil crust restoration, and microhabitat reconstruction

For areas with potential and mild rocky desertification, ecosystems still have relatively strong natural recovery capacity. Forest protection and the reduction of human disturbance should therefore be the main measures. Where necessary, mixed planting of native trees, shrubs, and herbs can be used to promote community recovery. Excessive dependence on a single tree species should be avoided.

In areas with moderate rocky desertification, soil and vegetation degradation is more evident. Vegetation restoration should therefore be combined with soil improvement. Drought-tolerant and nutrient-tolerant native plants can be selected and arranged according to local conditions. These measures can gradually improve soil and water conditions and support further vegetation recovery.

In areas with severe rocky desertification, restoration is limited by fragmented soil patches, low water availability, and habitat fragmentation. Large-scale afforestation is therefore less suitable. Instead, microhabitats such as rock fissures, depressions, and valleys with relatively better soil and water conditions should be used first. Drought-tolerant shrubs, herbs, and pioneer plants can be introduced through localized or patch-based restoration. The restored areas can then gradually expand into surrounding habitats.

In very severely degraded areas, soil is extremely limited, making it difficult to establish trees and shrub communities directly. Restoration should first focus on improving surface microenvironments and increasing their stability. Mosses and other pioneer organisms can retain water, accumulate organic matter, and improve local microhabitats. They can therefore create better conditions for later plant establishment (Liu et al., 2026). A gradual restoration pathway from “mosses/biological soil crusts → herbs → shrubs” can thus be explored for these highly degraded areas.

5. Problems and Future Directions

Current ecological restoration of karst rocky desertification still faces several problems, including limited differentiation among restoration strategies, relatively simple plant selection, and incomplete restoration evaluation systems.

First, areas with different levels of rocky desertification differ greatly in soil conditions, water availability, rock exposure, and vegetation structure. However, existing restoration approaches do not always provide sufficient differentiation among these levels. Restoration strategies that match different stages of degradation have not yet been fully developed.

Second, economic forests or single-species plantations are still widely used in some areas. These approaches can provide certain economic benefits, but long-term dependence on a single species may result in simple community structures and low species diversity. This can reduce ecosystem stability. In particular, the roles of mosses, biological soil crusts, pioneer plants, and microhabitats such as rock fissures, depressions, and valleys in severely and very severely degraded areas are still not well understood. Their relationships with later community succession also require further study.

Third, current restoration assessments often focus on vegetation indicators such as vegetation cover and biomass. Less attention is given to soil quality, water retention, biodiversity, and ecosystem functions. As a result, existing assessments may

not fully reflect the overall recovery of ecosystems.

Future studies should therefore give greater attention to differentiated restoration according to degradation level, targeted restoration based on microhabitats, and more comprehensive evaluation of ecosystem recovery.

Conclusion

The geological conditions of carbonate rocks, complex terrain, seasonal rainfall, and shallow soils provide the basic environmental conditions for rocky desertification. Inappropriate land use and vegetation destruction can further increase soil erosion and create negative feedback among vegetation, soil, and water conditions. Therefore, rocky desertification management should consider both the drivers of ecological degradation and the resulting ecological changes.

Vegetation recovery can improve soil quality and water retention, while appropriate community structures can strengthen soil and water conservation and ecosystem stability. Microhabitats also provide important conditions for plant establishment and community succession. Therefore, ecological restoration should move beyond simply increasing vegetation cover and focus on the recovery of ecosystem structure and functions.

Different levels of rocky desertification have different ecological limitations and therefore require different restoration strategies. Mild areas should mainly rely on protection and natural recovery. Moderate areas should strengthen coordinated vegetation and soil restoration. Severe areas should give greater attention to microhabitat restoration. Very severe areas should explore the early restoration roles of mosses, biological soil crusts, and pioneer plants. In this way, a better match can be established among rocky desertification level, habitat conditions, plant selection and arrangement, and restoration measures. Combining this approach with restoration at the microhabitat, slope, and small watershed scales can improve the targeting and long-term stability of ecological restoration in karst rocky desertification areas.

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