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Assessing Ecological Restoration in Arid Mining Regions: A Progressive Evaluation System

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Abstract: The mining activities in arid regions have resulted in significant ecological environmental issues, exacerbating the already challenging ecological conditions and leading to severe ecosystem damage. Merely relying on natural recovery processes proves inadequate, thus necessitating the implementation of artificial restoration measures to facilitate ecosystem recovery in these arid mining regions. However, it is difficult to scientifically answer the questions of how artificial restoration can be effectively combined with natural recovery, and to what extent can artificial assistance can define the beginning of natural recovery in ecosystems. To address this issue, this study proposed a stepwise ecological restoration model for arid mining regions. The model delineated the ecological restoration process in arid mining regions into three phases: "artificial reconstruction", "auxiliary ecological restoration", and "natural recovery", and constructed an evaluation index system of the stepwise ecological restoration process. Taking an example of a mining ecological restoration in Aksu, Xinjiang, this study examined the evaluation effects of the stepwise ecological restoration model on ecological restoration projects in arid mining regions. The research showed that adopting the stepwise ecological restoration model in arid mining regions can achieve scientific and moderate artificial restoration, better clarify ecological restoration goals, and facilitate the implementation of ecological restoration projects.

Keywords: arid mining areas; ecological restoration; stepwise ecological restoration; evaluation system

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1. Introduction

The extraction of resources in mining areas poses significant challenges to sustainable environmental development and ecological equilibrium. Mining activities extensively remove the topsoil layer, causing damage to the terrain and resulting in soil impoverishment and erosion, which in turn have adverse effects on vegetation growth [1,2]. Furthermore, the occurrence of frequent geological disasters damages the ecological and geological environment of mining areas, resulting in varying degrees of ecological damage and ecosystem degradation. This phenomenon hampers the mining region's capacity for self-recovery and resilience against external disruptions, thereby posing challenges to the preservation of ecological equilibrium [3]. Particularly in arid regions, these problems are exacerbated by the harsh ecological conditions. Arid regions inherently possess fragile ecological environments; due to the shortage of water resources, low precipitation, and sparse vegetation, it is difficult to form the basic conditions needed for the effective protection of surface soil and water. The self-recovery time cycle of the arid mining region ecosystem can extend for several centuries [4]. Ecological challenges are particularly prominent in arid mining regions, rendering ecological restoration exceptionally arduous and demanding [5]. The restoration of ecological systems in mining areas constitutes a pivotal element in the enhancement of ecological functions within environmentally vulnerable regions. The circumstances surrounding ecological restoration in arid mining regions are grave, underscoring the imperative to expedite the restoration process.

In accordance with the principle of "Green Mountains are gold mountains" and the notion of "The life community of mountains, rivers, forests, farmlands, lakes, grasslands, and deserts (MRFFLGD)" [6], the goals of ecological restoration in mining areas have evolved beyond mere enhancements of ecological conditions to encompass the establishment of self-sustaining ecosystems, progressive advancement towards a novel ecological equilibrium, and the promotion of sustainable development within the local social economy. The evolution of ecological restoration projects is necessary to move beyond simple land reclamation and afforestation efforts towards a more comprehensive restoration of ecological functions; it also emphasizes the overall enhancement of ecosystems that have suffered damage or degradation [7,8]. The artificial restoration of mining ecosystems is extensively employed as a rapid and efficient approach in response to the substantial human interference experienced by these ecosystems. Nevertheless, upon the cessation of intervention, the ecosystem may undergo a reversion to a degraded state. Under the concept of Nature-based Solutions (NbS), ecological restoration emphasizes natural recovery as the main approach, supplemented by artificial restoration [9]. However, the restoration of mining areas is a complex and time-consuming process, making it difficult to achieve desired outcomes mainly through natural recovery within a limited timeframe. The inclusion of artificial restoration techniques has the potential to expedite the ecological restoration process in mining areas [10]. Artificial restoration and natural recovery both play important roles in the ecological restoration of mining areas, but there is controversy among different scholars about their relationship, which also raises scientific questions about how and when artificial restoration should be combined with natural recovery. Only by resolving the relationship between the two can we better promote the ecological restoration process in arid mining regions. One of the best solution methods may be to integrate artificial restoration with natural recovery in the ecological restoration process in arid mining regions. A new theoretical model is therefore needed to support this concept.

In addition, the evaluation of mining areas' environmental impact serves as the fundamental basis for implementing restoration and remediation efforts [11]. The effectiveness of ecological restoration is the key to evaluating the overall quality of ecological restoration, providing scientific guidance for decision-making and the subsequent management of ecological restoration [12]. In order to achieve the sustainable development of mineral resource development and ecological environment protection, it is necessary to conduct a fair evaluation of the ecological environment in mining areas and establish a scientific and sound evaluation system [13,14]. As a complex whole, the ecological system of mining areas is interrelated and mutually influenced by evaluation indicators [15]. However, most current research mainly focuses on selecting indicators from a limited number of ecological elements to evaluate the effectiveness of ecosystem restoration [16]. These studies exhibit a deficiency in addressing the holistic perspective in the context of ecological restoration, resulting in the emergence of problems such as narrow-minded goals, inadequate interconnectedness, and an absence of a comprehensive assessment of the mining area ecosystem as an integrated entity [17,18]. Consequently, there is a pressing requirement for a methodical and scholarly evaluation indicator system to tackle these challenges.

To fill the gap, this study established a stepwise ecological restoration model in arid mining regions as a response to the aforementioned issues. The ecological restoration process of arid mining regions was categorized into three stages: "artificial reconstruction", "auxiliary ecological restoration", and "natural recovery". By adopting progressive restoration and management methods for damaged ecosystems in arid mining regions, scientific and moderate artificial intervention can be achieved to answer the question of how artificial restoration can be combined with natural recovery. A progressive ecological restoration evaluation system for this model was also constructed. Taking a mining area in Aksu, Xinjiang as an example, the constraints in each stage of the ecological restoration process in the mining area were comprehensively considered to evaluate the ecological restoration effect of each stage in order to solve the ecological problems that arise during the restoration process of the mining area and improve the ecological restoration effect of arid mining regions. The proposal of the stepwise ecological restoration model in arid mining regions is expected to provide a reference for the evaluation and engineering acceptance of ecological restoration in arid mining regions.

2. Stepwise Ecological Restoration Model in Arid Mining Regions

The stepwise ecological restoration strategy is a sequential and incremental restoration and governance framework that adheres to ecological principles and considers the historical context and present circumstances of regional ecological deterioration, while also acknowledging social investment and technological limitations [19]. In contrast to conventional one-time ecological restoration methods, stepwise ecological restoration entails dividing the restoration process into distinct phases, with emphasis on the gradual and systematic rehabilitation and management of impaired ecosystems. This approach encompasses the examination of obstacles encountered at every phase, the gradual implementation of diverse ecological restoration measures, the ongoing enhancement and rehabilitation of the compromised ecosystem, and the formulation of the most appropriate ecological restoration and governance strategies. Such an approach serves to mitigate the expenses and hazards linked to ecological restoration, heighten the precision of issue identification, expand the range of restoration techniques, and mitigate the likelihood of failure associated with singular ecological restoration plans.

Owing to the multifarious and capricious nature of ecological processes, the condition of an ecosystem undergoes perpetual fluctuations. When scholars engage in discourse pertaining to the species composition or habitat quality within an ecosystem, they commonly allude to the ecological circumstances at a particular juncture. In arid mining regions, distinguished by severe ecological conditions, a plethora of ecological restoration obstacles are encountered. These challenges manifest dissimilarly at different stages of restoration, rendering the exclusive evaluation of the ultimate restoration outcome ill suited for the intricacies inherent to arid mining region ecosystems. The challenges encountered during the restoration process vary across different stages, and relying solely on the evaluation of the final restoration outcome is inadequate to address the intricate nature of arid mining region ecosystems. Furthermore, these difficulties pose a hindrance to the formulation of the most appropriate restoration strategies and methodologies in such regions.

Therefore, this study proposed a new stepwise ecological restoration model in arid mining regions, which aims to address the ecological problems and restoration challenges in such regions. The model took into account the historical conditions and current ecological degradation issues in arid mining regions. It divided the ecological restoration process into three distinct stages, namely “artificial reconstruction”, “assisted ecological restoration”, and “natural recovery” (Figure 1). The model involved breaking down the ecological restoration process into segments, analyzing the key limiting factors at each stage, setting clear restoration goals for each stage of ecological restoration engineering, and scientifically implementing gradual restoration methods. The model enabled a more effective combination of artificial restoration and natural recovery, promoting the self-restoration of ecosystems, and contributing to achieving the sustainable development goals of ecological restoration in arid mining regions.

2.1. Artificial Reconstruction

Artificial reconstruction pertains to the implementation of artificial remediation and governance strategies within extensively impaired mining ecosystems, with the objective of expeditiously reinstating topography and land productivity. Mining operations impose substantial anthropogenic disturbances upon mining area ecosystems, leading to diverse levels of impairment and disturbances to natural surroundings, encompassing geological characteristics, hydrology, biodiversity, and soil. Mining operations have led to topsoil stripping, severe damage to terrain and landforms, uneven surfaces, and the formation of large mining pits. The slope of a mining pit is steep, making it prone to geological disasters such as collapse. Moreover, mining waste and household waste accumulate in the pits, polluting groundwater resources, leading to sparse and barren vegetation, and serious soil erosion problems. Especially in arid regions, rainfall is scarce, soil salinity is high, and salinization is a serious problem. The magnitude of environmental degradation has surpassed the inherent ability of the ecosystem to naturally regenerate. Consequently, the feasibility of self-recovery through ecological functions is rendered unattainable, thereby necessitating the implementation of artificial reconstruction methods to remediate extensively impaired mining area environments.

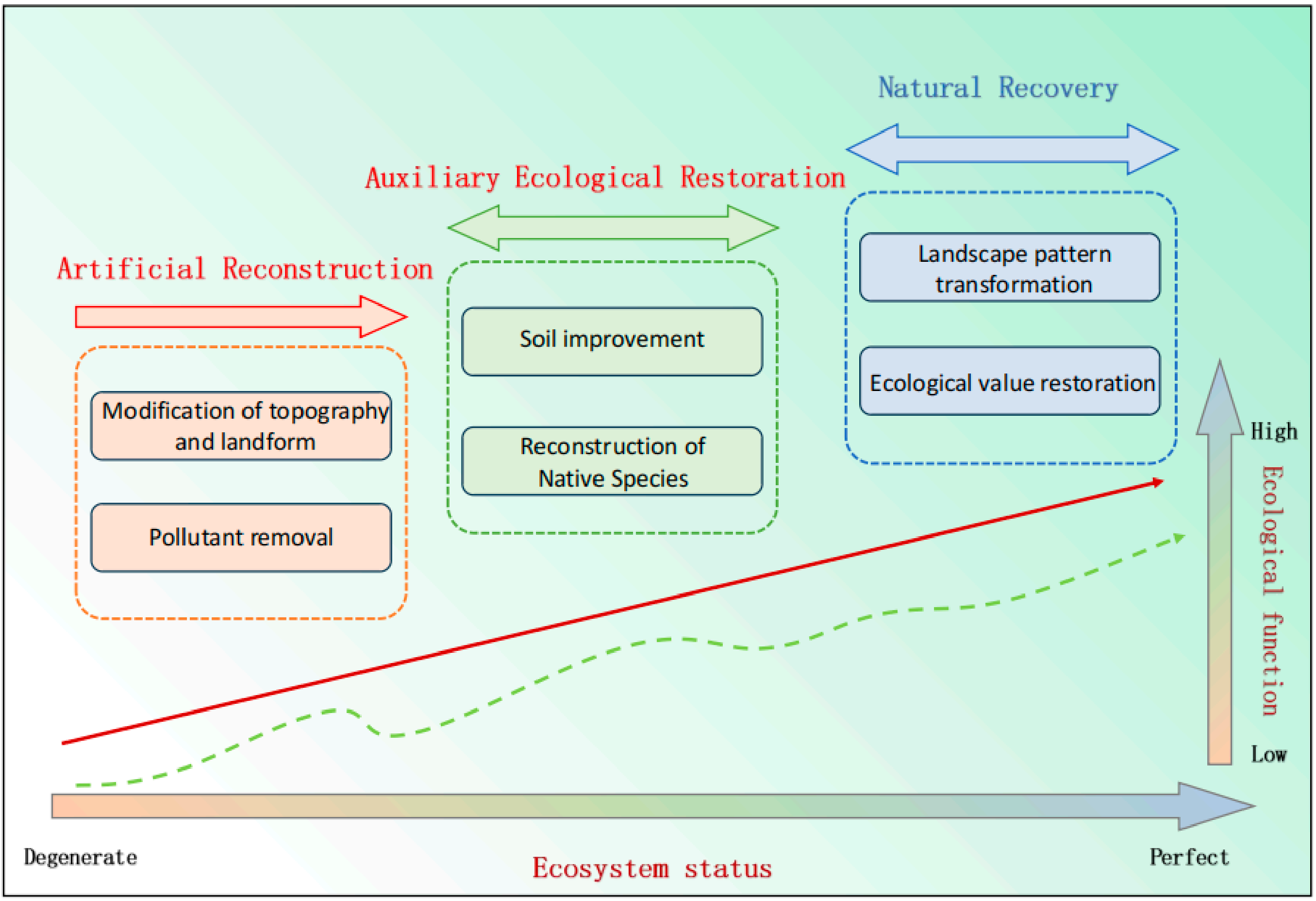

Figure 1. The stepwise ecological restoration model for arid mining regions.

The initial phase of the stepwise ecological restoration model in arid mining regions involves artificial reconstruction, which aims to address limiting factors, restore baseline ecological conditions, and facilitate positive ecological succession [20]. Consequently, when undertaking ecological system reconstruction in arid mining regions, it is imperative to prioritize the modification of topography and landform, along with enhancing the physical and chemical properties of the soil [21]. Through the implementation of landform reshaping and soil reconstruction techniques, geological disasters can be effectively prevented and controlled, thereby mitigating soil erosion and eliminating detrimental factors that impede vegetation restoration and land productivity. Furthermore, the utilization of earth backfill, fertilization, soil moisture-retaining agents, and soil conditioners is recommended to enhance soil structure and quality. These measures are intended to restore soil productivity and fertility in mining areas, thereby creating a conducive soil environment for optimal growth and development.

2.2. Auxiliary Ecological Restoration

Auxiliary ecological restoration, guided by ecological principles, is a methodology employed to restore extensively impaired ecosystems to their reference states, through a combination of biological, physical, and chemical restoration measures. The arid mining regions pose challenges to natural ecosystem recovery, primarily due to limited rainfall, high evaporation rates, and the hindered growth of vegetation. Consequently, the self-recovery of these ecosystems tends to be protracted. Auxiliary ecological restoration is implemented as the second phase of the stepwise restoration model in arid mining regions, following the artificial reconstruction that has effectively rectified the topography and enhanced soil conditions to a generally favorable state for vegetation growth. This stage capitalizes on the inherent recuperative potential of the impaired mining area ecosystem and incorporates a combination of biological and non-biological intervention strategies to expedite the restoration process [22].

The application of ecological principles for scientific plant selection and process management is crucial in the process of vegetation restoration in mining regions. This involves artificially planting vegetation, introducing anticipated species to facilitate positive ecosystem succession, enhancing biodiversity, improving ecosystem service functions and resilience, promoting the natural restoration of damaged ecosystems, and expediting their recovery cycles. In order to effectively rehabilitate various forms of degraded land, it is imperative to carefully consider the choice of pioneer species and appropriately suited species, as well as the arrangement of other vegetation. This is essential to guarantee the long-term stability of the reconstructed plant communities [23]. In arid mining regions, it is recommended to prioritize species that possess drought tolerance and adaptability to nutrient-deficient environments and exhibit robust germination capabilities and rapid growth. These key species, such as *Haloxylon ammodendron*, *Calligonum mongolicum*, and *Zygophyllum xanthoxylum*, play a pivotal role in the restoration of vegetation, which can accelerate and improve the efficiency of vegetation restoration.

2.3. Natural Recovery

Natural restoration is a phenomenon characterized by the sequential progression of natural succession and restoration, wherein the ecosystem's inherent self-regulatory and self-organizational capacities are harnessed following the cessation of human interference and the eradication of ecological coercive elements. Frequently, it denotes a governance approach aimed at attaining ecological restoration objectives through non-invasive or minimally invasive interventions [24]. Mildly degraded ecosystems, or heavily degraded ecosystems that have undergone significant ecological restoration measures, can depend on the inherent self-recovery capacity of the ecosystem to attain positive ecological succession. Once a mining area ecosystem attains a certain level of species communities and substantial enhancements in ecological conditions, it can naturally regenerate with the aid of its self-recovery capabilities. At this juncture, the ecosystem has the potential to advance towards self-renewal and positive succession, thereby enhancing ecological integrity and the functionality of ecosystem services. A comprehensive and robust ecosystem should exhibit ecological resilience, enabling it to promptly recover autonomously following disturbances. Adhering to the principle of prioritizing natural restoration as the primary approach, complemented by artificial restoration, aims to minimize the intervention and disruption caused by human intervention, ultimately reducing restoration expenses while maximizing the benefits of restoration. This approach aims to achieve a dynamic balance in the mining area ecosystem.

During the third phase of the stepwise ecological restoration process in arid mining areas, the management and protection of the natural recovery of the mining area ecosystem are implemented through measures such as enclosures and the prohibition of grazing. This stage encompasses the regulation of biological species' composition and structure, as well as the restoration of ecosystem functionality. This approach aims to enhance the ecological environmental quality of the mining area, elevate its ecological landscape functionality, and ensure the long-term stability and sustainable development of the mining area ecosystem by establishing a harmonious ecosystem that aligns with the surrounding landscape.

3. An Evaluation System of the Stepwise Ecological Restoration in Arid Mining Regions

The ecological environment of arid mining regions is subject to the influence of multiple factors and elements, necessitating the consideration of diverse indicators at each stage of ecological restoration in mining regions. Moreover, the effective delineation of the boundaries of various ecological issues poses a challenge, thereby impeding comprehensive evaluation [25]. The restoration of land production capacity and the sustainable utilization of abandoned land in mining areas have emerged as prominent development objectives for mining countries worldwide. However, there is currently a lack of a standardized restoration model and set of objectives [26]. To address this gap, it is crucial to establish a comprehensive indicator system that can accurately identify key limiting factors. This will enable a more scientific assessment of the effectiveness of restoration efforts in mining regions and facilitate a smoother ecological restoration process [27]. The assessment of ecological restoration in mining areas should encompass not only the impact of mining on the surrounding environment, but also take into account a comprehensive range of factors, including the structure, function, process, and services of the ecosystem. Additionally, it is crucial to consider various aspects such as the environmental background of the mining area and the challenges associated with restoring and governing the mining area [28]. Hence, in order to develop an assessment framework for evaluating the effectiveness of ecological restoration in arid mining regions, it becomes imperative to partition the ecological restoration goals of the mining site into distinct indicators capable of capturing the holistic state of these objectives. It is crucial to carefully select pertinent evaluation factors and establish evaluation criteria based on the restored or well-restored habitats surrounding the mining area.

To achieve a reasonable evaluation of the ecological restoration effect in arid mining areas, this study established a progressive evaluation system. The primary challenges in the ecological restoration of a damaged ecosystem are the alterations or diminishment of biological species and their respective habitats [29]. In arid mining regions, mining operations have resulted in detrimental effects on the soil environment, including severe erosion, land resource depletion, and hindered recovery efforts. Additionally, the harsh climatic conditions and water scarcity in these areas impose limitations on vegetation growth, rendering the ecosystem more vulnerable and less adaptable to external fluctuations. Vegetation, being a crucial constituent of arid ecosystems, serves as a perceptible manifestation of the natural milieu and a comprehensive representation of the regional ecological environment. The restoration of vegetation stands as a paramount approach in rehabilitating mining areas [30], while also serving as a direct and pivotal indicator for assessing land degradation attributes [31]. This article employed the concept of vegetation community succession and limiting factors to propose a method for categorizing the restoration stage of arid mining areas, with vegetation growth serving as a crucial criterion. The ecological restoration stage was further delineated through the monitoring of vegetation growth.

Based on engineering cases analyses and literature studies [25,32–34], this study selected four evaluation indicators, including soil physical and chemical properties, plant community characteristics, ecological restoration management, and landscape pattern benefits. It also selected the evaluation factor that best reflects the ecological restoration effect from each indicator to construct an evaluation system, as shown in Table 1.

(1) Soil physical and chemical properties

As fundamental evaluation indicators, soil physical and chemical properties can reflect the soil fertility and health status. The quality of soil's physical and chemical properties directly affects the growth of plants in mining areas, thereby affecting the effectiveness of ecological restoration. They mainly play a leading role in the artificial reconstruction stage and the auxiliary ecological restoration stage. In the artificial reconstruction stage, monitoring the physical and chemical properties of soil in the mining area can provide the necessary basis for vegetation growth in the later stage. The selected factors include soil particle size, soil thickness, soil moisture content, soil bulk density, soil fertility, soil pH, and soil conductivity.

Table 1. The ecological restoration effect evaluation system for arid mining regions.

Evaluation System	Primary Indicators	Secondary Indicators
A stepwise ecological restoration evaluation system for arid mining regions	Soil physical and chemical properties	Soil particle size Soil thickness Soil moisture content Soil bulk density Soil fertility Soil pH Soil conductivity
	Plant community characteristics	Emergence rate Plant height Plant community coverage Plant diversity indices
	Ecological restoration management	Plant maintenance effect Ecological restoration benefits Disaster prevention degree
	Landscape pattern benefits	Landscape aesthetics Landscape coordination degree

(2) Plant community characteristics

The plant community characteristics can accurately reflect the degree and benefits of ecological restoration, directly characterize the quality of the ecological environment, and play an important role in various stages of ecological restoration in mining areas. The factors selected in this study include emergence rate, plant height, plant community coverage, and plant diversity indices.

(3) Ecological restoration management

The effectiveness of plant management affects the natural recovery progress and stability of the mining area ecosystem. At the same time, choosing the ecological restoration benefits and disaster prevention degree is also an important manifestation of the ecological restoration effect on and environmental transformation of the mining area in the first two stages.

(4) Landscape pattern benefits

The transformation of the landscape in the mining area and the degree of landscape coordination between the mining area and the surrounding ecological environment can reflect the changes in the ecosystem service value of ecological restoration projects and should also be an important reference for evaluating the restoration results in the natural recovery stage. Therefore, landscape aesthetics and landscape coordination degree are selected as evaluation factors.

As a result of the intricate and protracted process involved in the restoration of mining areas, extant ecological restoration techniques may not invariably succeed in reinstating the structure and functionality of impaired ecosystems to their pre-disturbance state. Consequently, it becomes imperative to judiciously identify suitable reference ecosystems, taking into account the distinct social, economic, and environmental circumstances of the afflicted mining area, in order to establish appropriate restoration objectives for abandoned mining areas with varying degrees of degradation. This study utilizes the "International Principles and Standards for Ecological Restoration Practice (Second Edition)" in conjunction with the "Ecological recovery wheel" [35] and establishes a novel assessment framework tailored for arid mining regions (Figure 2). The framework documents the alterations in ecosystem characteristics at various stages in the mining areas, assesses the extent of ecological restoration, and provides enhanced monitoring of the restoration process.

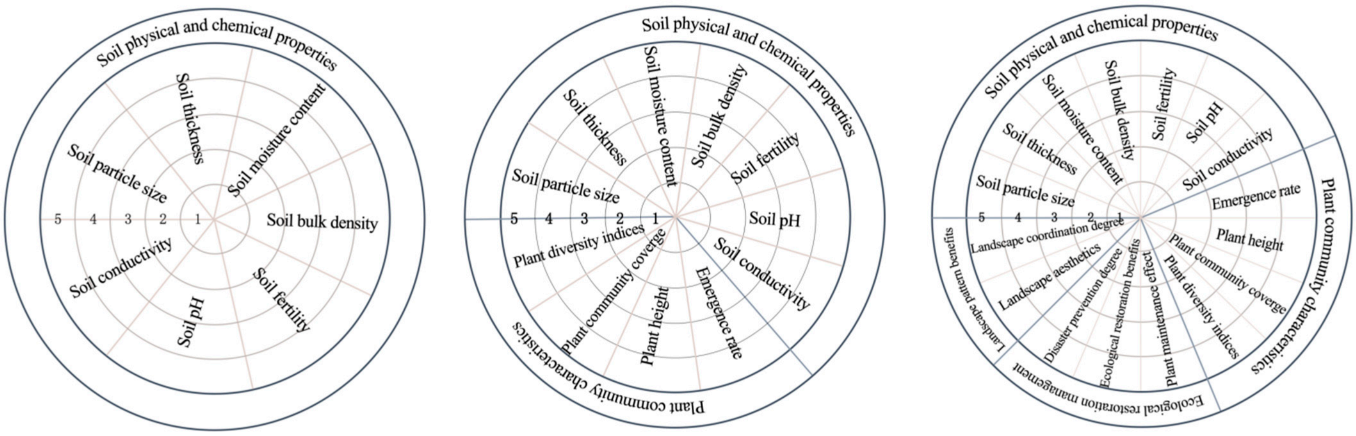

Figure 2. Ecological recovery evaluation wheel for arid mining regions. Note: The numbers 1–5 represent the degree of restoration in the ecosystem compared to the reference model, and the higher the number, the higher the degree of restoration.

4. A Case of the Stepwise Ecological Restoration

The ecological restoration case under consideration is situated in Xinjiang, a representative arid region in northwest China. The mining activities conducted in this area have led to significant environmental issues, resulting in extensive harm to the ecological system of the mining site and posing challenges for subsequent ecological restoration efforts. In 2021, the Aksu region of Xinjiang initiated the comprehensive conservation and rehabilitation initiative for the vital source region of the Tarim River (Aksu River Basin). One of the objectives of this endeavor is to undertake ecological restoration activities in the abandoned sand and gravel mines within the Aksu Prefecture, with the aim of mitigating geological hazards and reinstating ecological functionalities.

The case was conducted in Jiamu Town, Wensu County, Aksu Prefecture (Figure 3). These activities have resulted in significant ecological damage, persistent soil erosion, and a diminished capacity for environmental self-recovery within the pit. The irregular shape of the restoration area, characterized by steep walls and frequent collapses, exacerbates the situation. Furthermore, the removal of a large portion of topsoil has adversely affected surface vegetation, while the haphazard disposal of construction and household waste has further compromised the integrity of the terrain and landforms. The restoration area exhibits limited vegetation growth due to the detrimental effects of mining activities on the original ecological environment. Consequently, a substantial portion of land has become unusable and incapable of being developed in any capacity. This lack of coordination with the surrounding environment poses a significant threat to nearby water conservancy structures and negatively impacts the safety of agricultural activities in the surrounding farmland. Moreover, this situation results in a significant waste of available land resources, thereby constraining local planning, construction, and development efforts.

4.1. Artificial Reconstruction

In May 2022, we conducted a comprehensive on-site investigation to examine the geological and ecological conditions of the mines in the restoration area. The investigation elucidated the necessity of implementing ecological restoration and management measures, commencing with “artificial reconstruction”, to address issues such as degraded soil texture and extensive damage to the terrain and landforms within the pits.

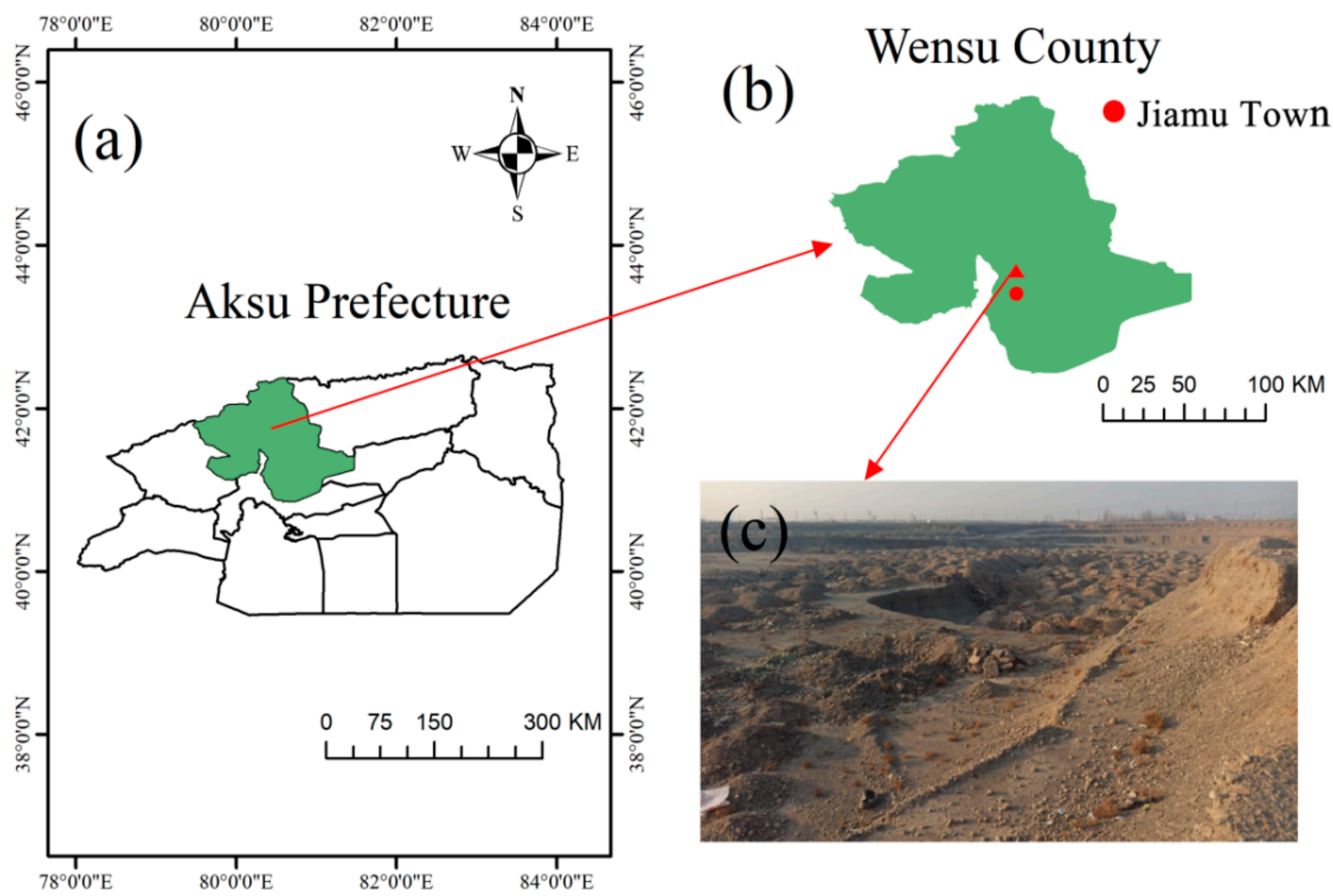

Figure 3. Overview of the geographical location of the restoration area. Note: (**a**) schematic diagram of the location of Wensu County in Aksu Prefecture; (**b**) schematic diagram of the location of the mine pit location in Wensu County; (**c**) the statte of the mine pit before restoration.

As a primary step, the removal and transportation of waste materials from the mining pits in the restoration area were carried out. Subsequently, the incline of the mining pit was adjusted to decrease the slope angle, thereby facilitating the integration of the restoration area with the surrounding environment and mitigating the potential hazards of geological disasters within the mining pit. Consequently, land leveling and soil enhancement measures were implemented, aiming to augment soil content and optimize the ratio of soil particle sizes (Figure 4). These interventions effectively addressed the issues of excessive gravel content, insufficient fine soil content, and inadequate organic matter within the mining pit, thereby establishing essential prerequisites for the growth of vegetation (Figure 5).

4.2. Auxiliary Ecological Restoration

Following the establishment of fundamental conditions for vegetation growth through the process of "artificial reconstruction", ecological restoration progressed to the phase of "auxiliary ecological restoration". The primary objective of this stage was to reinstate the vegetation within the restoration area, facilitating the introduction of desired species to foster a positive trajectory of ecosystem succession, encourage the natural recovery of impaired ecosystems, and expedite the overall restoration cycle. In March 2023, vegetation restoration work was carried out in the restoration area. We opted to employ *Fructus hippophae* as the plant species for ecological restoration. *Fructus hippophae* exhibits not only drought resistance and wind–sand resistance but also the ability to thrive in saline-alkali soil. Moreover, its fruit holds significant economic value, contributing to the financial gains of local farmers. To minimize human interference, measures such as drip irrigation belts and the establishment of fences were implemented after planting the seedlings. Additionally, the restoration area was diligently maintained and managed to guarantee the survival of plants and the efficacy of ecological restoration efforts. As of July 2023, the survival rate of *Fructus hippophae* forests in the restoration area had exceeded 70% (Figure 6).

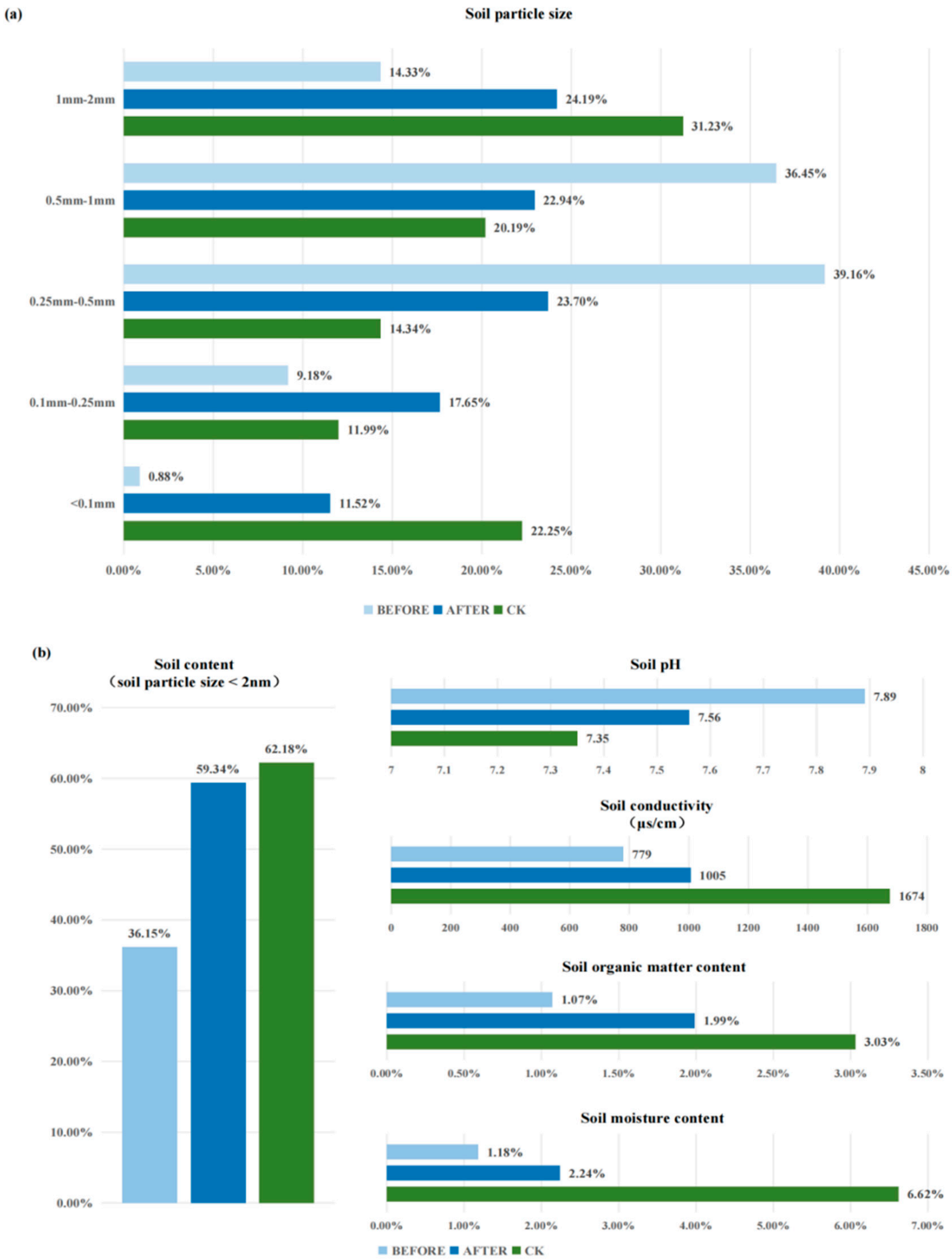

Figure 4. Comparison of soil physical and chemical properties before and after restoration. Note: (**a**) comparison of soil particle size before and after restoration; (**b**) comparison of soil content, soil pH, soil conductivity, soil organic matter content, soil moisture content before and after restoration.

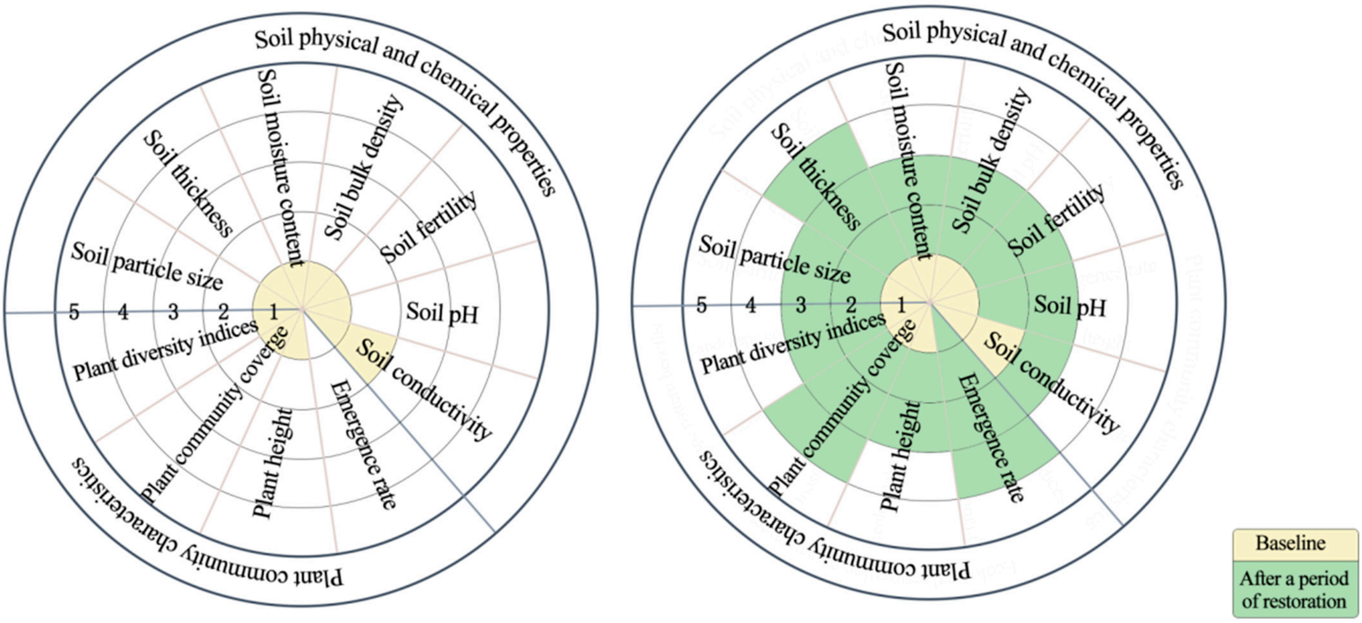

Figure 5. Comparative evaluation of growth conditions before and after mining area restoration. Note: The numbers 1–5 represent the degree of restoration in the ecosystem compared to the reference model, and the higher the number, the higher the degree of restoration.

Figure 6. Comparison of photos before and after mining area restoration.

4.3. Natural Recovery

With the ongoing enhancement of the ecological environment, the restoration area has progressed towards a stage of "natural recovery". As manual intervention decreases, indigenous plant species such as *Kali colinum*, *Haloeton glomeratus*, and *Alhagi camelorum* have emerged within the restoration area. The composition and community structure of plants in the restoration area have experienced continuous improvement, resulting in enhanced biodiversity, ecosystem integrity, and ecological service functions. Moreover, the area's self-recovery capacity and ecological resilience have been significantly strengthened. The implementation of this project has restored and improved the ecological environment of the mining area, effectively controlled soil erosion and desertification, and enhanced ecosystem functions such as soil and water conservation (Figure 7).

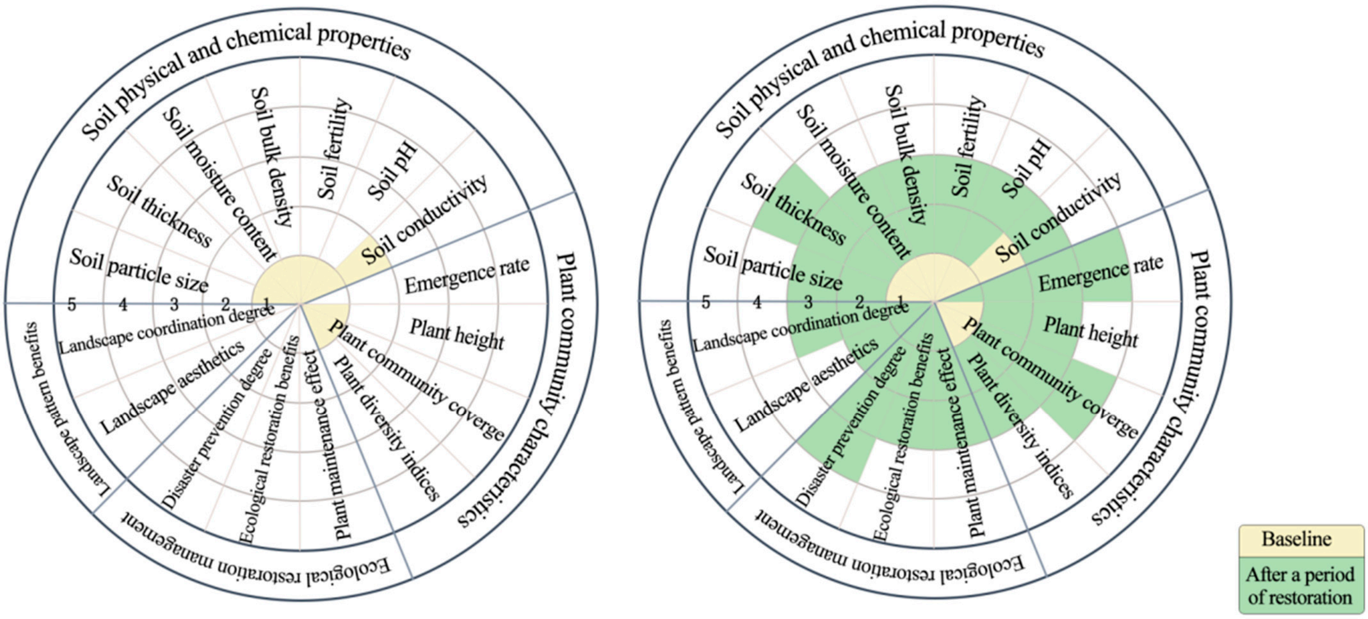

Figure 7. Evaluation of comparative effects before and after mining area restoration. Note: The numbers 1–5 represent the degree of restoration in the ecosystem compared to the reference model, and the higher the number, the higher the degree of restoration.

5. Discussion

5.1. Reflection on Ecological Restoration in Arid Mining Regions

The exploitation and utilization of mineral resources have been instrumental in fostering economic growth. However, this practice has also resulted in significant ecological degradation and environmental contamination, thereby impeding the progress of economic and social development in arid regions [36]. The essential goal of ecological restoration in mining areas is to restore the necessary ecological service functions of damaged ecosystems [37]. In the ecological restoration of arid mining regions, it is necessary to consider the degree of ecosystem degradation and the history and current situation of the mining area [38]. The physical conditions of mining have experienced substantial alterations and are ill suited for accommodating present and future ecosystems. Hence, the prioritization of the "future" state of the ecosystem over the "historical" state should be emphasized in the restoration of mining areas [39]. The restoration of mining areas is a continuous and dynamic task, and ecological restoration in mining areas should focus on establishing an ecosystem that can be maintained for a long time [40]. It is necessary to continuously monitor, evaluate, and adjust according to the actual situation. When formulating ecological restoration goals and evaluation standards for mines, environmental constraints must be given priority consideration. The ecological restoration process in different regions and types of mining areas faces different environmental problems and ecological complexity;

therefore, it is necessary to develop restoration goals and evaluation standards that are in line with local conditions [41,42]. It is crucial to avoid setting excessively high recovery goals in arid mining regions to ensure the practicality and feasibility of recovery measures.

The stepwise ecological restoration model and progressive evaluation system proposed in this study attempt to provide new ideas for future scientific research. Dividing ecological restoration projects into different stages is conducive to clarifying more scientific and achievable ecological restoration goals, thereby promoting the further development of ecological restoration projects. This approach divided into stages can better manage and supervise the implementation process of ecological restoration projects, making them more targeted and effective. Meanwhile, in practical engineering applications, the evaluation system should be adjusted according to the characteristics and changes of the specific mining area restoration project. When selecting evaluation indicators, it is necessary to fully consider the characteristics of the mining area ecosystem, the setting of restoration goals, feasibility and operability, and other factors to ensure the accuracy and credibility of the evaluation results. Only in this way can the effectiveness of ecological restoration projects in mining areas be better reflected, providing scientific bases for the further improvement and optimization of ecological restoration strategies.

5.2. The Problems Faced by Vegetation Restoration in Arid Mining Regions

The restoration of vegetation through natural succession alone is a long and challenging process, making it difficult to achieve the restoration of system structure and function [43]. Vegetation reconstruction is the main means of ecological restoration in mining areas, but it is constrained by many influencing factors [44,45] mainly manifested in the high cost of vegetation restoration due to water scarcity in arid mining areas. Although seed sowing is simple and feasible, the drought in these regions, coupled with their low precipitation, high evaporation rate, and insufficient soil fertility, makes it difficult for seeds to germinate, posing obstacles to growth [46]. This study conducted the transplantation of *Fructus hippophae* seedlings into the mining area; while this can effectively contribute to short-term restoration, its extensive adoption in arid mining regions is hindered by its high cost and subsequent maintenance requirements [47]. During the entire process of establishing *Fructus hippophae* forests, irrigation was used to increase soil moisture content and promote plant growth, undoubtedly increasing the cost of ecological restoration. Moreover, the arid mining area has high soil salinity, and the application of irrigation can lead to the migration and accumulation of soluble salts on the soil surface, thus forming saline-alkali soil [48].

In addition, the selection of vegetation restoration is also the key to the success or failure of ecological restoration in arid mining regions. For example, the adult plants of *Populus euphratica Oliv.* exhibit a robust capacity to acclimate to aridity and salinity, whereas their seedlings lack such advantages and necessitate adequate water for survival [14]. In the absence of human intervention, the majority of species tend to experience a decline due to environmental stresses or natural calamities [49]. Therefore, in the restoration of mining areas, it is often necessary to choose local eugenic indigenous species to ensure ecological benefits; how to select suitable indigenous species in fragile habitats and make reasonable allocations are also important key points.

5.3. The Application of Gravel in Ecological Restoration in Arid Mining Regions

In the ecological restoration project of mining areas, this study believes that restoring the gravel soil layer on the surface is also one of the effective restoration methods. In arid mining regions, excessive emphasis on improving vegetation coverage often leads to high reconstruction costs. And, irrigation is needed to ensure the survival and growth of plants, making it difficult to widely apply in arid mining areas, which also leads to a contradiction between high investment in environmental protection and low efficiency in vegetation restoration. After mining, a large amount of coarse gravel is produced, which plays an important role on the soil surface. The gravel layer on the soil surface can effectively prevent soil erosion, reduce the occurrence of wind erosion and sandstorms, and thus protect the stability of the soil. The gravel layer also helps to increase soil permeability, promote soil water infiltration and retention, reduce direct sunlight on the soil surface, lower soil temperature, and thus slow down the water evaporation rate, which is beneficial for maintaining soil moisture and fertility [50,51]. Therefore, in the absence of water sources and funding, restoring the surface gravel soil layer in ecological restoration projects in mining areas is also an effective restoration method, but the ratio of gravel particle size and the application of gravel still needs further research.

6. Conclusions

This study proposed a new stepwise ecological restoration model suitable for arid mining regions, dividing the ecological restoration process of arid mining areas into three stages: “artificial reconstruction”, “auxiliary ecological restoration”, and “natural recovery”. It is a specific practical exploration in the field of arid mining area restoration, adhering to the basic principle of “natural restoration as the main focus and artificial restoration as the auxiliary”. This study helps to address the controversial issues and uncertainties between artificial restoration and natural recovery.

This study constructed a progressive evaluation system and took the ecological restoration project in a mining area in Aksu, Xinjiang as an example, and analyzed the specific application of the stepwise ecological restoration model in ecological restoration projects in arid mining regions. The results indicated that adopting phased ecological restoration in arid mining areas can achieve scientific and moderate artificial restoration, better clarify ecological restoration goals, and facilitate the implementation of ecological restoration projects.

The stepwise ecological restoration model and progressive evaluation system emphasized gradual recovery and governance, achieving scientific and moderate manual intervention. This study aims to improve the pertinence, operability, and effectiveness of restoration work by fully utilizing the advantages of combining artificial restoration and natural recovery. It also needs to be applied and confirmed in the ecological restoration of arid mining regions. We hope that this study can provide a valuable reference and foundation for scholars engaged in ecological restoration work in arid mining regions.

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