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Index System to Evaluate the Quarries Ecological Restoration

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Abstract: The restoration and evaluation of degraded ecosystems is an important component of the sustainable development of complex "human-natural-economic" ecosystems. Based on an analysis of ecosystem evolution and the integration of structure, function, and services, this study proposes that ecosystems can be returned to a self-maintaining, dynamic balance by enriching system elements, strengthening the relationships between the different elements and diverse ecological processes, and restoring internal functions, which includes the self-regulation of degraded ecosystems. This study developed and categorized quarry ecosystem recovery indicators based on the Core Capabilities of the Society for Ecological Restoration (SER) International through literature review and the development of recovery plans. Metrics identified in the literature were validated through the recovery plan review and the case study, and based on the findings, a user-friendly checklist for practitioners was established. Three elements and 17 indicators representing ecological processes, vegetation structures, and ecological functions were developed to evaluate and manage the ecological restoration of an abandoned quarry.

Keywords: quarry; ecological processes; vegetation structure; ecological function; ecological restoration; restoration evaluation; index system

1. Background

The excessive use of natural resources by human societies has increased the stress on natural ecosystems and resulted in climate change, environmental pollution, vegetation damage, biodiversity loss, etc. The constant acceleration of urbanization and industrialization worldwide, along with the accompanying demand for mineral resources, has led to the development of new quarries that have largely destroyed many natural ecosystems [1]. Quarrying results in significant visual and ecological impacts [2], not all of which have been identified [3]. Quarrying drastically destroys flora and fauna, thereby reducing biodiversity and disrupting fundamental ecological relationships. Moreover, it extensively damages soil by modifying the original site topography and depleting and altering soil microbial communities [3–7]. Because ecosystem degradation has increased in severity, investigations into ecosystem restoration are urgently required.

Although human technology cannot restore natural systems, it can be applied to improve natural restorations by introducing important plants and animals into ecosystems to generate the basic habitat conditions and promote natural evolution and ecosystem recovery. Thus, many quarries implement rehabilitation or reclamation actions that benefit biodiversity [8–10]. Rehabilitation seeks to repair one or more ecosystem attributes, processes, or services. Reclamation, on the other hand, includes land stabilization, public safety guarantees, aesthetic improvement, and usually a return of the ecosystem considered useful in the regional context [11,12].

However, whether recovery is occurring during the process of restoration can be unclear due to a lack of relevant reports and research. Ecological restoration assessment takes a specific target and system as a reference and evaluates the changes in structure, function, quality, health, and safety [13], and studies have indicated that ecological restoration evaluations play an important role in promoting restoration ecology as an area of scientific research [14–16]. Thus, a set of generally accepted criteria should be defined for use by ecologists and project engineers so that they can evaluate the success of ecological restorations in restoration projects [17], as a set of guiding criteria will greatly promote the evaluation of restoration projects and the reporting of recovery results [18].

The key to evaluating ecological restoration lies in the selection of the evaluation indicator and the construction of the indicator system. Methods of comprehensively and objectively selecting the evaluation indicator and scientifically designing the indicator system represent a hot topic in the field of ecological restoration and evaluation [19].

2. Literature Review

Diamond (1987) [20], who focuses on the restoration of vegetation, believes that ecological restorations can reconstruct a self-maintaining natural community and maintain its continuity, while Egan (1996, quoted in Hobbs and Norton, 1996) [15] indicates that ecological restoration is the process of reconstructing historical regional plant and animal communities and maintaining the sustainability of the ecological system as well as its traditional cultural functions. An ecosystem is affected by non-biological factors, such as solar energy, light, temperature, rainfall, wind, rock, soil, water, air, CO_2, O_2, N_2, inorganic salts, humus, proteins, and carbohydrates, as well as biological factors, such as producers, consumers, and decomposers. These factors are interrelated, and their roles constitute the entire functioning of the ecosystem and provide services for the environment and the functional maintenance of the ecosystem. The foundation for ecosystem restoration and construction is an increase in biodiversity, and plant diversity is particularly important. Sustaining plant diversity can increase the species diversity of ecosystems because high plant diversity promotes high productivity and provides a material basis for the ecological diversity of the ecosystem. Furthermore, different plant species within an ecological system can create a variety of heterogeneous habitats, which accommodate a greater number of species assemblages, and the multiple layers of roots of different plants lead to various soil micro-habitats that accommodate a diverse array of soil animals and microorganisms [21].

According to the vertical structure of its plant community, an ecological system can be divided into several layers, such as trees, shrubs, herbs, and the surface layer (mosses and lichens) [22]. The tree layer has tall stems and foliage, which perform photosynthesis and regulate gas exchange. Leaf transpiration can inhibit high temperatures and increase air humidity to adjust the microclimate. Trees, shrubs, and herbs combine to form a landscape, which provides scenic and recreation services for society. In the community ecosystem, pollination and seed dispersal for reproduction can be conducted via wind energy. Green plants primarily produce energy via photosynthesis and chemical energy bacteria to provide a variety of crops, fruit, prey, and other resources for consumers (human beings and animals). The plant community is the primary producer, and it is also the habitat of animals. The ground layer (lichen or moss and other plants) can be used for water penetration and as an adsorbent for water conservation to achieve efficient water regulation. The soil is held in place by the root systems of plants, thereby preventing soil collapse and soil erosion. Microorganisms and fungi in the soil decompose biological debris to generate, store, and accelerate the internal cycle of nutrients.

Therefore, the natural ecological recovery process is essentially the synergy of the evolution of the soil and plant systems, and the degree of ecological restoration can be most directly represented by the characteristics of the soil and vegetation in different phases [23]. As for the indicators used to evaluate recovery, it must first be possible to repeatedly measure and assess them over time. Second, indicators should be sensitive to changes in the status of the recovery of the community over time or within key ecosystems, which allows for interactions to be explored. Third, the effects of community- and individual-level experiences also should be considered concurrently [24].

Quarries produce sand and stone used for different purpose, and sandstone ore is generally exposed at the surface. Therefore, most sandstone mining is open-pit mining. Thus, the surface vegetation and soil must first be stripped off during excavation. During this process, the entire quarry ecosystem is degraded and disappears, primarily due to man-made interference and damage to the ground vegetation. Anthropogenic deforestation and mining has resulted in the destruction of the vegetation community structure, biodiversity reductions, soil erosion, and ecosystem degradation. Mining induces damage to vegetation, exposes the soil layers and leads to soil erosion and soil loss, and forest felling is another primary factor that causes vegetation degradation. Vegetation degradation is a dominant factor driving soil erosion, and both combine to drive the simplification of ecosystem elements and ecological processes. So, it is important to reconstruct the ecosystem and quantify the ecological success of the restoration project.

Ecological restoration assessment is defined by three concepts: evaluation of the results, evaluation of the effects, and evaluation of the benefits. Results evaluation is a comparison with the stated goals or reference system and focuses on the recovery of the ecosystem composition, structure, and pattern. Effect evaluation refers to whether the recovery of the ecological system has positive or negative impacts on other aspects of the environment, such as the influence of vegetation restoration on the water, atmosphere, soil, and other organisms. Benefit evaluation refers to the social, economic, and ecological values following ecosystem restoration. In other words, results evaluation emphasizes the restoration of ecosystem structure and the integrity of the ecosystem; effect evaluation emphasizes the recovery of ecosystem function, that is, the recovery of energy flow, material circulation, and information transfer, which affect ecosystem balance and stability; and benefit evaluation emphasizes the recovery of ecosystem services, that is, the recovery of the capacity to provide services for humans and promote socioeconomic and environmental change, which reflect ecosystem externalities [13].

Quarry mining results in severe environmental damage, which requires a long period of time to undergo a recovery cycle. Therefore, when evaluating ecological recovery, the priority should be to consider the changes in ecosystem composition, structure, and pattern; that is, results evaluation should be dominant. Once the result evaluation is established, and the effects and benefits evaluations can be carried out in the follow up.

3. Methods

3.1. Indicator Development

In this study, potential indicators were initially identified through a systematic review of the literature and categorized based on the Core Capabilities of the Society for Ecological Restoration (SER) International [12]. After aggregating the identified indicators, several methods were used to validate the final list including reviews of the literature, quarry or mining reclamation plans, and recovery plan case studies from CNKI (the largest Chinese literature database) and the Web of Science. A flow chart of the methodology follows (see Figure 1).

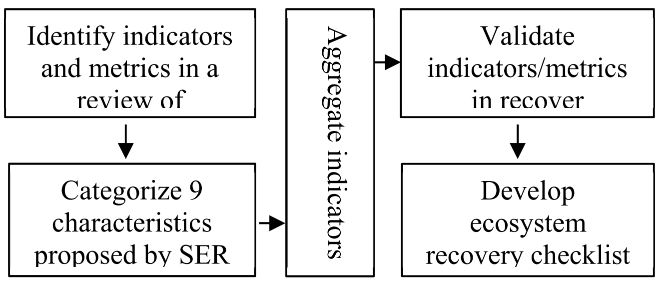

Figure 1. Methods used to develop and validate recovery indicators for the quarry recovery checklist.

The ecosystem recovery literature was systematically reviewed to identify research related to measuring the recovery progress to extract potential recovery indicators and metrics. First, citations were obtained from mine and quarry reclamation and recovery management scheme reports, and second, a supplemental University of Tsinghua Libraries Articles+ search was conducted using the keywords "quarry," "recovery," and "ecosystem." A total of 22 scholarly, peer-reviewed articles published between 2010 and 2017 were retrieved from the CNKI database, all of which involved environmental science and resource utilization, mining engineering, building science and engineering, agricultural disciplines, etc. Using the keywords "ecological," "restoration," and "quarry" to search the Web of Science database, a total of 60 meetings, five reviews, and 128 articles published between 2010 and 2017 were retrieved. Altogether, a total of 118 peer-reviewed publications and conference presentations were reviewed to determine if they incorporated metrics or measures to gauge the progress of ecosystem recovery (Table 1).

Table 1. The checklist and the corresponding SER Core Capabilities and recovery focus areas.

Core Capability	Recovery Focus Area	Total Number of Indicators
		Literature Review
soil physical and chemical properties	Topsoil sickness, soil texture, organic matter Water content, pH value, compactness Soil quality, available NPK, soil organic carbon	Fei et al., 2009 [25]; Wang, 2009 [26]; Zhang, 2013 [23]; Rivera et al., 2014 [27]; Redente et al., 1997 [28]; Holmes, 2001 [29]; Chenot et al., 2017 [11]; Song, 2008 [30]; Chen, 2009 [31]
terrain	Gradient, slope direction Slope damage and slope formation time	Wang, 2009 [26]; Zhang, 2013 [23]
climate	Rainfall; Temperature	Wang, 2009 [26]; Zhang, 2013 [23]
	Irrigation Condition	
vegetation	Ratio of native plants to evergreen tree species Vegetation cover, woody plant cover Evenness of trees and shrubs Species diversity, species richness Litter structure Existing vegetation cover Root system status, community structure	Fei et al., 2009 [25]; Zhang, 2013 [23]; Song, 2008 [30]; Liu et al., 2014 [13]; Li, 2010 [32]
biodiversity	Animal and plant species richness Biological abundance Existing species	Xu and Chen, 2008 [33]; Hao et al., 2016 [34]; Zhang, 2015 [35]

(SER means Society for Ecological Restoration; N means nitrogen; P means phosphorus; K means kalium)

Ruiz-Jaén and Aide (2005) [36] summarized and analyzed articles published on "restoration ecology" over 11 years following the founding of the discipline (1993–2003) and found that species diversity, vegetation structure, and ecological processes are the main measures of ecological recovery. In terms of species diversity, researchers typically considered plants in their ecological recovery indicators, which accounted for 79% of the articles, while arthropods accounted for 35%. Vegetation coverage, density, biomass, and height are common measures of vegetation structure and corresponded to 62%, 58%, 39%, and 39% of the studies, respectively. In the research of ecological processes, the use of biological interactions as the ecological recovery indicator accounted for 60%, followed by soil deposits (47%) and organic matter (39%) [30].

Abandoned quarries generally consist of four parts: (1) the quarry rock, that is, the bare wall remaining after ore mining; (2) the stone pit, that is, the pit that forms as quarrying progresses; (3) rock dumps, which are produced by the stripping of the topsoil and rubble during the mining process; and (4) the storage and transportation platform, that is, the ore deposit, processing, and transport platform, which is an area of flat land after mining. The factors that restrict quarry recovery are shown in Table 2.

Table 2. Structural characteristics and key elements restricting the ecological restoration of quarries.

Structure	Characteristics	Key Ecological Restoration Elements
waste stacking yard	Stacked stripped topsoil and mining gangue. Loose sand and gravel structure with a gentle gradient. Facilitates plant rooting and growth.	Soil matrix improvement. Topsoil restoration. Gentle gradient to promote survival of the flora. Vegetation restoration is the key element.
remaining excavation slope	Gentle gradient, usually between 40 and 70 degrees. Hard rock and stone with scant soil on top.	Soil matrix improvement. Reinforcement of the slope and fixation of surface soil to ensure habitat for flora.
platform or pithead	Hard rock remaining after the excavation of the stone.	Soil matrix improvement. Soil dressing to form a soil profile at least 20-cm thick on the platform surface.
stonewall	Smooth slope surface and steep gradient without any soil.	Restore soil. Hang net spray grass and incorporate comprehensive slope engineering technology.

3.2. Indicator Validation

As a first step in validating the indicators identified in the literature, quarry recovery plans whose contents had been analyzed for another project were reviewed to determine whether the indicators were used in practice. Sixty-nine recovery plans had previously been collected from all of China and included the quarries in Beijing City [23,30,37,38], Chongqing City [39], Guangdong Province [40], Hunan Province [31], Zhejiang Province [26,41], Guangxi Province [42], Jiangsu Province [43,44], and so forth; these plans were included in this study if they scored above the overall mean in the original plan quality assessment [45]. Each of these plan-based indicators could be categorized within aggregate indicators, illustrating that all of the plan-based indicators validated the existing literature-based indicators. Table 3 shows the quarries with recovered ecosystems and validated recovery evaluation indicators.

Table 3. The validated recovery evaluation indicators.

Quarry Location	Author	Track Time	Recovery Evaluation Indicator
Beijing, Changping, Fangshan District	Zhang, 2013 [23]	2a	Soil, plant species, Simpson and Shannon indicators
Beijing, Miyun County	Li, 2010 [32]	13a	Plant community structure, soil physical and chemical properties
Beijing, Fangshan, Huangyuan Village	Zhang et al., 2013 [38]	1–3a, 3–5a, 5–10a	Species importance value, diversity, richness, and evenness
Beijing, Fangshan, Ligezuang Village	Liu, 2011 [37]	2a	Soil seed bank, plant community structure
Beijing, Mentougou District, Xishan	Song, 2008 [30]	1, 5, 15, 32a	Soil seed bank and physical and chemical properties, community structure
Zhejiang Province, Zhoushan City	Chang and Wang, 2011 [46]	6a	Soil physical and chemical properties
Hunan Province, Hengyang City	Chen, 2009 [31]	50a	Plant community structure and species, Shannon and Simpson indicators
Shandong Province, Zibo City	Han et al., 2008 [47]	50a	Plant community characteristics
East China region	Wang, 2009 [26]	25a	Soil physical and chemical properties, plant community structure
Hubei Province, Huangshi City	Shao et al., 2014 [48]	3a	Soil physical and chemical properties

Table 3. *Cont.*

Quarry Location	Author	Track Time	Recovery Evaluation Indicator
Beijing, Mentougou District, Danli Village	Shi, 2014 [49]	8a	Soil chemical properties, plant and insect community structure
Beijing, Mentougou District	Hong, 2008 [50]	20a	Vegetation distribution and condition
Southeastern Mediterranean	Chenot et al., 2017 [11]	Decades	Topsoil and soil seed bank
Galapagos Islands	Trueman et al., 2013 [51]	60 years	Vegetation structure
Southeastern France	Dutoit et al., 2013 [52]	30 years	Plant community and soil physical and chemical properties

Therefore, based on the above validated evaluation indicators and the Core Capabilities proposed by SER International, we consolidated the ecosystem restoration evaluation indicators as follows (see Table 4).

Table 4. Indicator system to evaluate quarry ecological restorations.

Elements	Indicators	Indication
Ecological Process Indicator	Top soil sickness Soil bulk density/soil moisture Soil available N, P, K Soil organic matter Soil enzyme activity	Bearing capacity Water/fertility retaining ability Soil productivity/carrying capacity
Vegetation Structure Indicator	Species of arbor layer Species of shrub layer Species of herb layer Shannon diversity index Ecological dominance indicator Pioneer species Constructive species	System productivity Energy storage and conversion capacity Community structure and function Ecological niche diversity
Ecological function indicator	Soil microbial diversity Soil microflora diversity Soil fauna functional group diversity Biomass	Niche diversity Diversification of decomposition process and material circulation Material cycle diversification

The plan-based indicators were then reviewed to identify potential metrics to be added to the list of possible measurements, and the case studies highlighted the potential use of the recovery indicators by a community to evaluate recovery success based on actual recovery experiences. The validation of the indicators through case studies may elucidate potential sources of data to evaluate the ongoing ecosystem recovery of a quarry as well as its pre-disaster baseline status. In addition, the case studies may help further demonstrate how local planning can be used to fulfill national recovery priorities as outlined in the Core Capabilities.

4. Results and Discussion

Ecological processes are interrelated; an ecological system can achieve "structure-function-service" integration. From the above mentioned, we found that the indicator system used to evaluate an ecological restoration must be composed of three aspects: vegetation structure, ecological process, and ecological function (the soil physical and biochemical characteristics and subsurface water system are already included in the ecological process). Among the ecological process indicators, the soil thickness, quality, parent material (lithology), and physical and chemical properties characterize the soil-bearing capacity and soil fertility after restoring quarry waste dumps and the platform (or pithead) via soil dressing measures.

The nutrient and enzyme activities characterize the diversification of the soil material cycling process and the carrying capacity of the land [35]. The effects of an ecological restoration are usually measured by the attributes of ecological systems, such as the biodiversity, vegetation structure, and ecological processes [9,53]. The quantity of biological species, the rate of biomass increase, the soil physical and chemical properties, etc. are among the recognized indicators of ecological restoration [34,54]. The soil seed bank is the sum of all seeds surviving in the aboveground litter and the soil [55] and represents the latent phase of the plant population. On the one hand, the ground vegetation is the direct provenance of many species in the soil seed bank, and the biological rhythm and seasonal changes in the ground vegetation influence the composition, size, and dynamics of soil seed banks. On the other hand, seeds in these banks can participate in the natural regeneration of the ground vegetation by germinating and forming sturdy seedlings, which directly affect the structure, composition, and biodiversity of the ground plant community [56,57]. Changes in the soil properties, nutrient cycling, and biological interactions are ecological processes that can reflect the success of an ecosystem restoration. The recovery of biological interactions is essential for long-term ecosystem functioning.

In the vegetation structure indicator, the Shannon diversity indicator is used to estimate the diversity of a community. When only one population is observed in the community, the Shannon indicator is equal to 0; when there are more than two populations in a community and only one member in each population, the Shannon indicator reaches the maximum value. The Shannon diversity indicator is a good method of characterizing the statistics of community diversity in an ecosystem restoration; therefore, it is suitable for evaluating ecological restorations. Dominant species have the highest number of individuals in each layer of the community and are the most important species in the layer because these species have the largest ecological role and determine the basic characteristics of the layer. The edificatory plant is the dominant species in the upper layer of a plant community, and it is usually the community constructor. The constructive species determines the appearance of the community and restricts other components of the community (including plants, animals, and microorganisms). Therefore, the species included in the restoration of ecological systems must be considered, and constructor species are important in the evaluation of the restoration scheme. The purpose of the restoration project should be to restore the most dominant species in the primary functional groups, rather than a specific number of species [58]. This method is practical and can achieve the most important goal, which is achievable in most recovery projects. Pioneer species are species in the early stages or in the mid-stage of the succession of ecological communities. Pioneer species appear earlier and survive relatively easily, and they play a constructive role in the ecological restoration of communities in the ecological restoration framework. However, the maximum biological diversity method can be used to conduct artificial restorations, which eliminates the need to introduce pioneer species. However, in areas where recovery is relatively difficult or where the habitat conditions are not sufficient, the emergence of pioneer species plays an important role in community construction. The vegetation structure indicator represents the community ecosystem productivity, the energy storage and conversion capacity, and the ecological niche diversity and its complicated functions in the community ecosystem. The restoration of vegetation communities is a prerequisite for the restoration of animal communities and ecological processes. Therefore, vegetation communities can be considered evaluation indicators, and they are easy to measure with low processing time.

Among the ecological function indicators, soil organisms regulate ecological processes, such as decomposition, nutrient mineralization, etc., and microorganisms play an important role in the ecosystem by participating in nutrient cycling, organic matter degradation, and energy flow. The generation cycle of arthropods is short; therefore, these organisms can reflect inter-annual variations in the recovered plots. Small arthropod species can effectively monitor subtle but important diversification factors that may affect the habitat quality. The flora community impacts the arthropods' food structure, habitat, natural enemy species, population dynamics, and fecundity, which then affects the diversity and richness of the plant communities. However, the diversity of the arthropod community also influences the structure, function, stability, and ecological processes of the ecosystem [59]. Arthropods directly or indirectly use the vegetation as food and habitat; therefore, they are sensitive to disturbances in the composition of the plant community. Changes in the diversity and complexity of the arthropod community could reflect habitat degradation; therefore, these organisms could play a role as a large-scale ecosystem biodiversity indicator in the evaluation of ecological restoration projects.

5. Conclusions

Quarry mining devastates vegetation and the related ecosystem functions; thus, vegetation restoration may be severely restricted by site conditions. In addition, plant recovery is usually slow and the remaining plants may persist in the grass and shrub stages for a long time. For natural restoration and long-term ecological restoration, the "plant community characteristics" are more suitable for use as the recovery evaluation indicator, and the proportion of native species is suitable for characterizing the degree of degradation of the ecosystem because such restorations tend to correspond to the succession of the original habitat.

In a quarry, the surface soil may be stripped, which destroys the local vegetation community and greatly reduces the number of species. Due to the lack of soil and nutrients, low soil activity and serious soil erosion are key factors limiting ecological restorations of quarries. Soil is the foundation for the ecological restoration of the vegetation community. For areas where the soil has been stripped off the surface, the soil layer thickness is the most important recovery factor. The soil physical and chemical properties, structure, and nutrient indicators in the current recovery assessment indicator can be directly referenced to select the quarry soil recovery evaluation index, and soil microbes, including the soil macrofauna and soil bacteria, provide important ecological functions for the recovery of the plant-soil system. Soil microorganisms can help community reconstruction and increase feedback in the material circulation and energy flows in the ecosystem processes on the ground or underground, and their behavior is indicative of soil dynamic recovery, which is conducive to promoting the recovery and cohesion of all ecological processes.

The restoration of the ecological system of the abandoned quarry represents the restoration of self-maintaining and self-regulating functions within a complex "human-natural-economic" ecosystem, which is influenced by human disturbances and natural factors. The ecosystem management of quarries focuses on the recovery of the ecosystem "structure-process-function" integration, which can stimulate the self-repair function of the ecosystem and eventually generate an ecosystem that exhibits a dynamic balance and the relative stability of self-maintenance. The preliminary evaluation indicators described above were selected for the evaluation of degraded ecosystem restorations. However, to improve and test the indicators to determine their usefulness in restoration evaluations and monitoring system construction, the indicators must move beyond a theoretical discussion and be implemented in practical investigations to determine whether they can promote research on the evaluation, monitoring, early warning, and restoration of degraded ecosystems caused by human interference.

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