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Comparative Study on Ecological Restoration Effectiveness in Mining Areas Based on FVC: A Case Study of the Maoming Open-Pit Mine

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Abstract— *To improve the ecological condition of the mining area, the Maoming Open-pit Mine in Guangdong Province launched a systematic ecological restoration project in 2013 to gradually restore the mining ecosystem. To quantitatively evaluate the effectiveness of the restoration, this study used Landsat series remote sensing images from 2013 to 2021 and applied the Pixel Dichotomy Model to estimate Fractional Vegetation Cover (FVC) as the primary evaluation indicator. The spatiotemporal dynamics of vegetation cover before and after ecological restoration were analyzed to quantitatively assess restoration effectiveness. The results show that: (1) The proportion of areas with low vegetation cover continuously decreased from 94.91% to 60.53%, whereas the proportion of areas with medium-high and extremely high vegetation cover increased from 0.11% to 29.16%. Vegetation recovery gradually spread from the periphery toward the interior of the pit. (2) The distribution of vegetation cover classes improved significantly, with a substantial reduction in bare soil areas and a marked increase in areas with medium and high vegetation cover, indicating a significant improvement in overall vegetation coverage. (3) Over the study period, the average vegetation cover in the mining area increased steadily from 1.18% to 18.00%, representing a substantial improvement in vegetation conditions. In conclusion, the restoration practices and outcomes of the Maoming Open-pit Mine provide valuable insights for the ecological restoration and post-restoration effectiveness assessment of similar legacy open-pit mines across China.*

Keywords*— *Maoming Open-pit Mine, Fractional Vegetation Cover (FVC), Dimidiate Pixel Model, Ecological Restoration, Remote Sensing Spatiotemporal Monitoring

I. INTRODUCTION

Mineral resources provide the material basis for economic development and are essential for ensuring national energy and strategic security. However, prolonged, large-scale, and intensive mining activities have inevitably caused severe damage to regional ecosystems, manifesting as vegetation loss, land degradation, soil erosion, and environmental pollution, thereby significantly undermining the stability of ecosystems within and surrounding mining areas. Against the backdrop of advancing ecological civilization, mine ecological restoration has become a critical component of environmental governance. Consequently, the scientific and quantitative assessment of restoration effectiveness has emerged as an important research focus [1][2].

Vegetation recovery is central to mine ecological restoration and plays a decisive role in the rehabilitation of ecosystem functions. Fractional Vegetation Cover (FVC) is widely recognized as an important indicator for evaluating vegetation growth and restoration status, providing an intuitive measure of restoration progress. As a simple yet effective indicator, FVC has been extensively applied to assess the effectiveness of mine ecological restoration [3]. Compared with conventional approaches, such as field surveys and monitoring stations, remote sensing technology enables cost-effective, large-scale, long-term, and dynamic monitoring of vegetation. It facilitates the rapid estimation of FVC across different periods, providing reliable technical support and data for comparative analyses of vegetation conditions before and after ecological restoration [4][5].

The Maoming Open-pit Mine is one of the most representative oil shale mining areas in southern China. Decades of intensive mining activities have severely degraded the local ecological environment, resulting in significant ecological problems. Mining operations not only caused air and soil pollution but also disrupted the original ecosystem structure, leading to habitat degradation and substantial biodiversity loss. Furthermore, the large open pit gradually filled with rainwater after mining activities ceased, forming a closed water body. Owing to the absence of effective inflow and drainage systems, the water quality continuously deteriorated, with pH, dissolved iron, cadmium, and other water quality indicators exceeding national standards. Locally known as the "Stinky Water Lake," it posed persistent pollution risks to surrounding soils and groundwater. In addition to surface water pollution, the groundwater system was also severely affected. Large-scale dewatering during mining operations caused substantial declines in groundwater levels, forming extensive cones of depression and desiccated zones that depleted regional water resources and disrupted domestic and agricultural water supplies. Meanwhile, highly acidic leachate generated from mine waste further contaminated groundwater, exacerbating environmental degradation [6][7]. Additionally, severe disturbance of the surface geological environment increased the risks of landslides, collapses, and debris flows [5].

Since the implementation of a systematic ecological restoration project in 2013, the ecological environment of the Maoming Open-pit Mine has gradually improved. Current research on this site has predominantly adopted multi-indicator approaches to investigate ecological changes, whereas studies focusing specifically on FVC as a single evaluation indicator—particularly those involving long-term, stage-specific, and spatially explicit comparisons—remain limited. To address this research gap, this study focuses on FVC and utilizes Landsat satellite imagery to estimate spatiotemporal FVC dynamics for a fine-scale assessment of vegetation restoration. The findings are expected to provide scientific support for the continued ecological management and optimization of restoration strategies at the Maoming Open-pit Mine, while also offering valuable insights for evaluating ecological restoration effectiveness in similar abandoned open-pit mines.

II. STUDY AREA AND DATA SOURCES

2.1 Overview of the Study Area

The Maoming Open-pit Mine, also known as the Maoming Oil Shale Open-pit Mine, is located in the northwestern part of Maonan District, Maoming City, Guangdong Province (Figure 1). It is the largest oil shale mining site in South China and was once a major driver of industrial development in the “Southern Oil City” [5][8]. The study area covers approximately 10.07 km², with the core pit occupying about 6 km² and reaching a maximum depth of more than 100 m. The landscape is characterized by a large abandoned open pit, northern and southern spoil dumps, and exposed rock waste piles [7].

Large-scale mining activities began in 1962 and ceased in 1993. Prolonged open-pit mining severely altered the original topography, nearly eliminated the native vegetation, and left extensive areas of bare land. Only drought- and infertile soil-tolerant herbaceous plants are sparsely distributed around the periphery of the mining area. The soil is primarily composed of rock waste, coke ash, and kaolin, and is characterized by a coarse texture, poor water and nutrient retention capacity, strong acidity, and localized heavy metal contamination, making the ecosystem highly fragile [1].

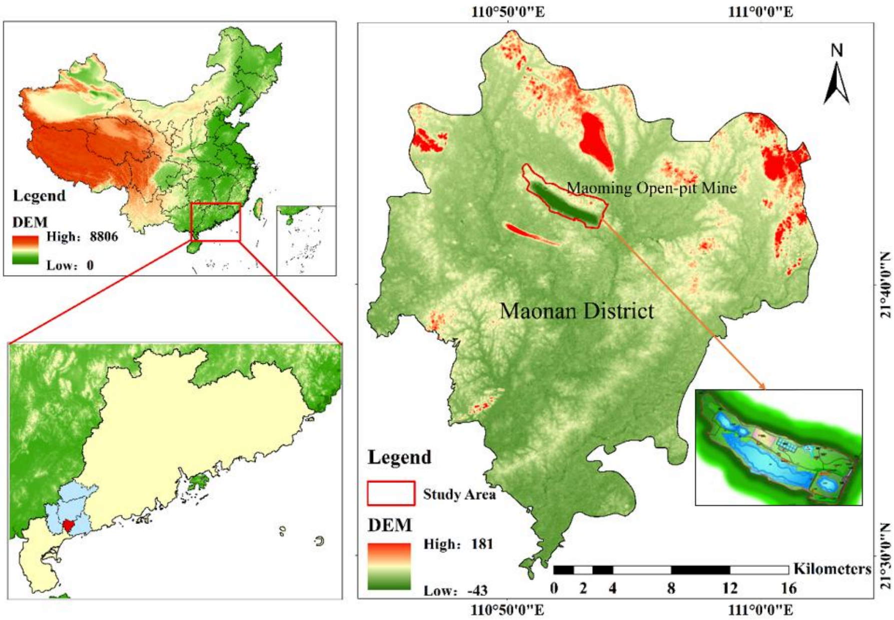

Fig.1 Location of the Study Area

To improve the ecological condition of the mining area, Maoming City launched a systematic ecological restoration project in 2013, with restoration efforts focusing primarily on vegetation restoration and ecological enhancement. First, a water diversion project was implemented to mitigate water pollution. Approximately 160 million m³ of water from the Gaozhou Reservoir irrigation canal was diverted into the mine pit lake and connected to the Xiaodong River, creating a dynamic water circulation system that mitigated the acidification of the accumulated pit water. Second, vegetation restoration was implemented by excavating planting pits and replacing the original soil with nutrient-rich soil to improve nutrient-poor substrates, followed by planting tree species tolerant of drought and nutrient-poor soils. Third, terrain and soil restoration included leveling spoil piles and rock waste dumps, eliminating slope instability hazards, and improving degraded soils. Fourth, a long-term maintenance program was established, with professional teams conducting pruning, pest control, replanting, and fertilization to ensure the long-term success of vegetation restoration. Through these restoration measures, more than 9,000 mu (approximately 600 ha) of land has been reforested, with over 500,000 trees planted [5].

By 2017, the core restoration areas had been largely completed, representing a transition in ecological conditions from severe degradation to functional recovery. This study encompasses the entire core mining pit and the northern and southern spoil dumps, covering the full period of ecological restoration and providing a robust data foundation for assessing spatiotemporal changes in vegetation cover and restoration effectiveness.

2.2 Data Sources

This study uses Fractional Vegetation Cover (FVC) as the primary indicator to evaluate the effectiveness of ecological restoration in the mining area. The datasets used in this study include remote sensing imagery and fundamental geographic data for the study area, obtained from the Geospatial Data Cloud and the National Geomatics Platform (Table 1).

For remote sensing analysis, five Landsat 8 OLI/TIRS satellite images acquired between 2013 and 2021 were used to calculate the Normalized Difference Vegetation Index (NDVI) and estimate FVC. Images with minimal cloud cover were selected from the Geospatial Data Cloud to ensure data quality and the reliability of the analysis. Standard preprocessing procedures, including radiometric calibration and atmospheric correction, were performed to ensure data accuracy. In addition, ancillary geographic datasets, including vector boundary data and administrative division maps, were used for image clipping, data extraction, and subsequent spatial analysis.

Table 1 Detailed Description of Data

Data Type	Specific Data Description	Data Source	Data Time	Data Purpose
Remote Sensing Data	Landsat 8 OLI/TIRS	Geospatial Data Cloud, https://www.gscloud.cn/	2013-2021	Calculate NDVI and retrieve FVC
Basic Geographic Data	Vector Boundary	Drawn based on remote sensing image interpretation	—	Used for remote sensing image clipping
	Administrative Division	National Geospatial Information Public Service Platform, https://www.tianditu.gov.cn/	—	Used to determine the location

III. RESEARCH METHODS

3.1 Technical Route

This study aims to evaluate the effectiveness of ecological restoration at the Maoming Open-pit Mine. Multi-temporal Landsat remote sensing imagery was processed and analyzed to estimate vegetation cover during different restoration periods within the study area. The resulting FVC datasets were then used to analyze spatiotemporal dynamics and conduct comparative assessments, thereby quantitatively evaluating restoration effectiveness. The overall methodological framework consists of the following steps: Data Acquisition → Data Preprocessing → FVC Estimation → Spatiotemporal Analysis → Restoration Effectiveness Assessment → Conclusions and Recommendations (Figure 2).

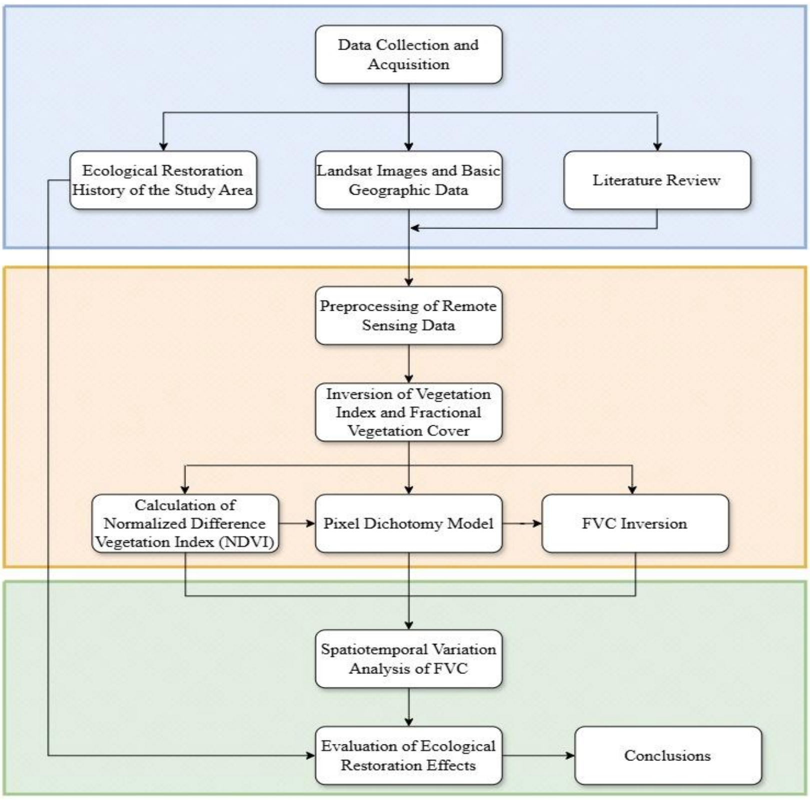

Fig.2 Technical Roadmap

3.2 NDVI Calculation

This study uses the Normalized Difference Vegetation Index (NDVI) to quantitatively assess vegetation cover in the study area. NDVI is one of the most widely used remote sensing indicators for characterizing vegetation growth status and surface vegetation conditions. It is calculated from the normalized difference between the reflectance values of the near-infrared and red bands and effectively reflects vegetation vigor, FVC, and overall vegetation health [8]. The NDVI is calculated using Equation (1):

$$NDVI = \frac{NIR-R}{NIR+R} \quad (1)$$

In Equation (1), NIR represents the reflectance in the near-infrared band, and R represents the reflectance in the red band. The values of NDVI range from −1 to 1, with higher values indicating denser vegetation cover and better vegetation growth conditions in the study area [9].

3.3 FVC Inversion

Fractional Vegetation Cover (FVC) is defined as the proportion of ground surface covered by the vertical projection of vegetation canopy. It is a key quantitative indicator for characterizing vegetation cover and assessing ecological quality [10]. In this study, the NDVI-based Pixel Dichotomy Model, a widely used method for FVC estimation, was employed to estimate fractional vegetation cover across the study area, thereby providing an accurate representation of vegetation conditions and ecological status. The fundamental assumption of this model is that each remote sensing pixel consists of a linear mixture of pure vegetation and pure bare soil, and that the spectral response of each pixel is a weighted combination of these two endmembers. Accordingly, FVC was calculated using the NDVI-based Pixel Dichotomy Model, as expressed in Equation (2):

$$FVC = \frac{NDVI-NDVI_{soil}}{NDVI_{veg}-NDVI_{soil}} \quad (2)$$

In Equation (2), NDVI represents the Normalized Difference Vegetation Index for an individual pixel; NDVIsoil represents the NDVI value of non-vegetated surfaces (e.g., built-up land, bare soil, and water bodies); and NDVIveg represents the NDVI value of fully vegetated areas. The theoretical range of FVC is 0–1 (or 0%–100%), representing the proportion of ground surface covered by the vertical projection of vegetation canopy within a unit area. In practical applications, following established methodologies, the 5% of the cumulative NDVI frequency distribution within the study area was used as NDVIsoil, whereas the 95% was used as NDVIveg. This approach effectively reduces the influence of noise and extreme values, thereby improving the stability and reliability of FVC estimation and providing a robust basis for subsequent analyses of spatiotemporal vegetation dynamics and ecological restoration effectiveness [11][12].

Based on the estimated FVC values, vegetation cover was classified into different grades with reference to the Technical Specification for Eco-environmental Status Evaluation and previous studies, while taking into account the characteristics of land degradation, vegetation loss, and ecological restoration in mining areas. This classification framework enables a comprehensive evaluation of restoration effectiveness and the spatial heterogeneity of vegetation recovery within the study area [13].

3.4 Spatial Pattern Analysis of FVC

Based on the FVC raster datasets estimated using the NDVI-based Pixel Dichotomy Model for the period from 2013 to 2021, this study analyzed the spatial distribution and temporal dynamics of vegetation cover in the mining area using the spatial analysis tools available in ArcGIS. According to the vegetation cover classification criteria, the FVC raster data for each study year were reclassified into five vegetation cover classes (Table 2) using the raster reclassification tool. Subsequently, graduated color symbology was applied to generate spatial distribution maps of vegetation cover for each study year. The resulting maps were then compared to analyze changes in the spatial distribution of FVC over time and to characterize its spatiotemporal evolution. This approach enables a systematic assessment of the effects of ecological restoration on vegetation recovery in the mining area from a spatial perspective and provides a reliable basis for evaluating restoration effectiveness [3].

Table 2 Classification of Vegetation Coverage Grades

Grand	Name	FVC Range
1	Bare Soil / No Vegetation Zone	0.00～0.10
2	Low vegetation coverage zone	0.10～0.30
3	Moderate vegetation coverage zone	0.30～0.50
4	High vegetation coverage zone	0.50～0.75
5	Extremely high vegetation coverage zone	0.75～1.00

IV. RESULTS AND ANALYSIS

4.1 Spatiotemporal Evolution of FVC

Based on the FVC spatial distribution maps (Figure 3) and the statistical results derived from the NDVI-based Pixel Dichotomy Model for the period 2013–2021, the study area exhibited pronounced spatial heterogeneity and substantial changes in vegetation cover structure. Overall, vegetation restoration followed a progressive pattern characterized by expansion from the peripheral areas toward the center of the mining area, accompanied by a transition from fragmented vegetation patches to more continuous distributions and from predominantly low vegetation cover to increasing proportions of medium and high vegetation cover. These patterns clearly illustrate the spatial progression of ecological restoration and the gradual recovery of vegetation.

From the perspective of spatial distribution, vegetation restoration exhibited a progressive expansion from the outer margins toward the central pit area:

(1) 2013 (Pre-restoration): Areas with low vegetation cover dominated the study area, with vegetation mainly confined to the northern boundary and the vicinity of central water bodies. Following decades of intensive mining, spoil dumps, rock waste piles, and pit slopes remained extensively exposed, resulting in severe degradation of the native vegetation and a highly fragile ecological environment.

(2) 2015 (Early restoration stage): Areas with medium and high vegetation cover began to appear on the eastern spoil dumps and along the northern water diversion channels, while areas with low vegetation cover gradually decreased. Vegetation expansion was particularly evident on gently sloping platforms in the eastern and northern parts of the mining area, where vegetation patches became increasingly connected.

(3) 2017 (Late restoration stage): Areas with low vegetation cover decreased substantially and were primarily confined to the steep southwestern slopes and untreated rock waste piles. Continuous vegetation cover developed across the eastern and northern spoil dumps as well as the gentle slopes surrounding the pit lake, with markedly improved connectivity among areas of high and very high vegetation cover.

(4) 2019 (Late restoration stage): Low vegetation cover continued to decline, whereas medium and high vegetation cover expanded steadily, forming relatively continuous vegetation zones around the spoil dumps and along the periphery of the pit.

(5) 2021 (Post-restoration): Areas with very high vegetation cover became concentrated on the eastern and northern spoil dump platforms and in the mature restoration zones. Medium and high vegetation cover further expanded toward the pit margins and secondary gentle slopes, whereas areas with low vegetation cover remained limited to isolated cliff faces in the southwestern part of the mining area and a few scattered rock waste piles.

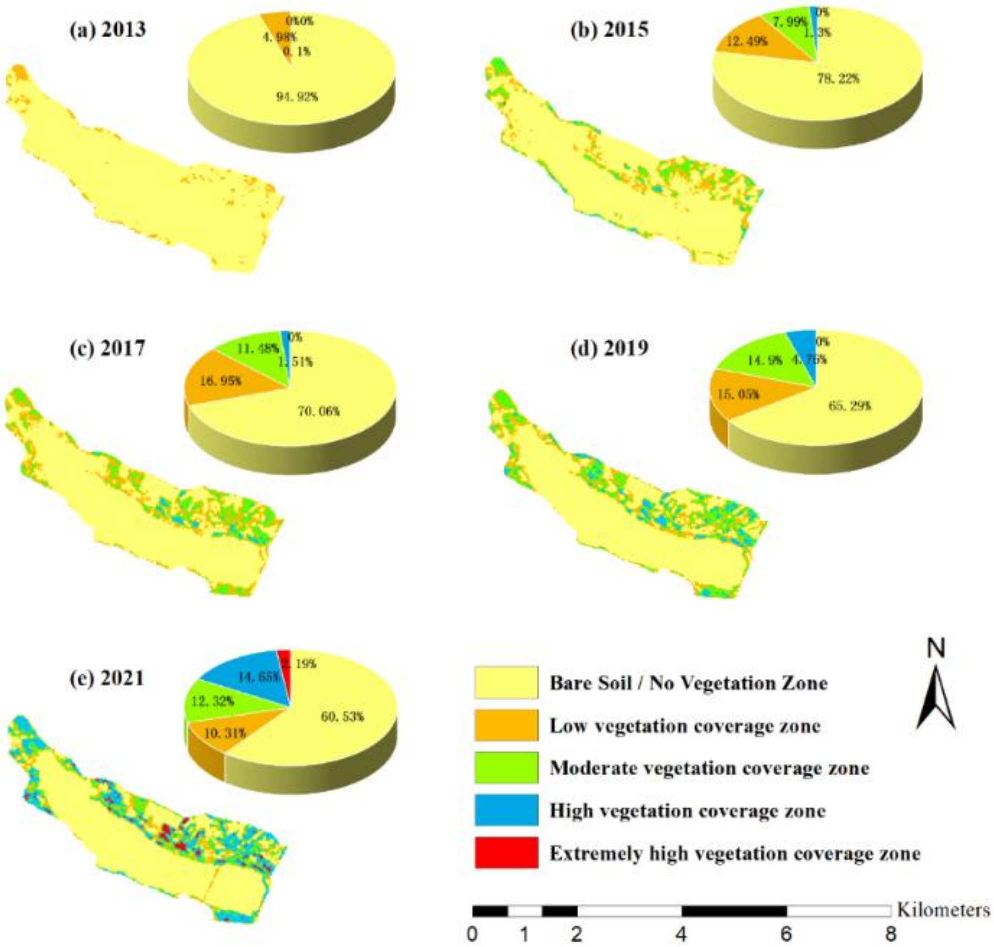

Fig.3 Spatial Distribution of FVC in the Study Area

From the perspective of vegetation cover structure, the proportions of the different FVC classes in the study area underwent substantial changes during the study period, consistent with the observed spatial evolution patterns. The statistical results derived from the NDVI-based Pixel Dichotomy Model further illustrate these changes. Table 3 summarizes the annual proportions of the different FVC classes, while Figure 4 presents their temporal variation.

(1) Non-vegetated/bare soil: As the dominant land cover type before ecological restoration, this class declined continuously from 94.91% in 2013 to 60.53% in 2021, indicating a substantial reduction in exposed surfaces and a marked improvement in site conditions following restoration.

(2) Low vegetation cover: This class increased from less than 5% in 2013 to approximately 10.3% in 2021. Although its proportion reached a maximum in 2017 and declined slightly thereafter, the overall increasing trend indicates that restoration measures effectively promoted the initial establishment of vegetation.

(3) Medium vegetation cover: This class accounted for only 0.1% of the study area in 2013 but increased steadily after the implementation of ecological restoration. Despite a slight decline after 2019, it reached 12.32% by 2021, exceeding the proportion of low vegetation cover and becoming the principal vegetation cover class contributing to ecosystem recovery.

(4) High and extremely high vegetation cover: Both classes were absent in 2013. High vegetation cover increased gradually between 2015 and 2017 before accelerating after 2019. By 2021, the combined proportion of high and extremely high vegetation cover reached approximately 15%, indicating the formation of relatively stable and continuous vegetation patches in parts of the

mining area. However, areas with extremely high vegetation cover remained limited, suggesting that vegetation restoration was still dominated by low and medium vegetation cover and that further ecological improvement is still possible.

Overall, the structural evolution of vegetation cover in the mining area was characterized by a continuous decline in non-vegetated/bare soil areas, rapid expansion of low and medium vegetation cover, and the gradual development of high vegetation cover. These changes closely corresponded to the implementation of ecological restoration measures and indicate a progressive transition from sparse and fragmented vegetation to increasingly continuous and well-developed vegetation communities. Furthermore, the observed increase in vegetation continuity and spatial stability demonstrates the positive effects of long-term ecological restoration on improving vegetation cover throughout the study area.

Table 3 Table of Area Proportions of Each FVC Grade

Year	Bare Soil / No Vegetation Zone	Low vegetation coverage zone	Moderate vegetation coverage zone	High vegetation coverage zone	Extremely high vegetation coverage zone
2013	94.91%	4.98%	0.10%	0.00%	0.00%
2015	78.22%	12.49%	7.99%	1.30%	0.00%
2017	70.06%	16.95%	11.49%	1.20%	0.00%
2019	65.29%	15.05%	14.90%	4.76%	0.00%
2021	60.53%	10.30%	12.32%	14.65%	2.19%

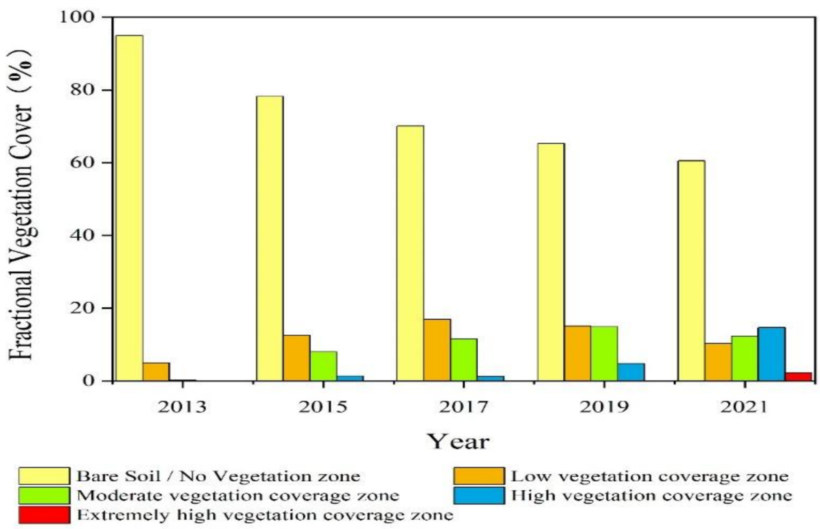

Fig.4 Statistical Chart of Area for Each FVC Grade

4.2 FVC Time-Series Variation Analysis

To quantitatively characterize the overall trend of ecological restoration in the study area, the mean FVC from 2013 to 2021 was calculated, and its interannual variation was illustrated in Figure 5. The results indicate that the mean FVC in the mining area increased substantially throughout the study period. Prior to the implementation of the ecological restoration project in 2013, long-term oil shale mining had resulted in extensive exposed surfaces and severe vegetation degradation, with the mean FVC measuring only 1.18%, reflecting an extremely fragile ecological condition.

Following the implementation of ecological restoration measures, vegetation cover improved steadily over time. By 2015, the mean FVC had increased to 6.68%, indicating the initial establishment of vegetation within the restored areas. In 2017, the mean FVC further increased to 8.99%, suggesting continued vegetation recovery. Thereafter, vegetation cover continued to improve, with the mean FVC reaching 18.00% by 2021. Overall, the mean FVC increased markedly throughout the restoration period.

Among the different restoration stages, the period from 2019 to 2021 exhibited the most rapid vegetation recovery. During these two years, the mean FVC increased by 6.04 percentage points, corresponding to an average annual increase of 3.02 percentage points, which was considerably higher than that observed during the other study periods. These results indicate that vegetation in the mining area progressively recovered from a severely degraded condition and highlight the positive effects of the ecological restoration project on vegetation recovery.

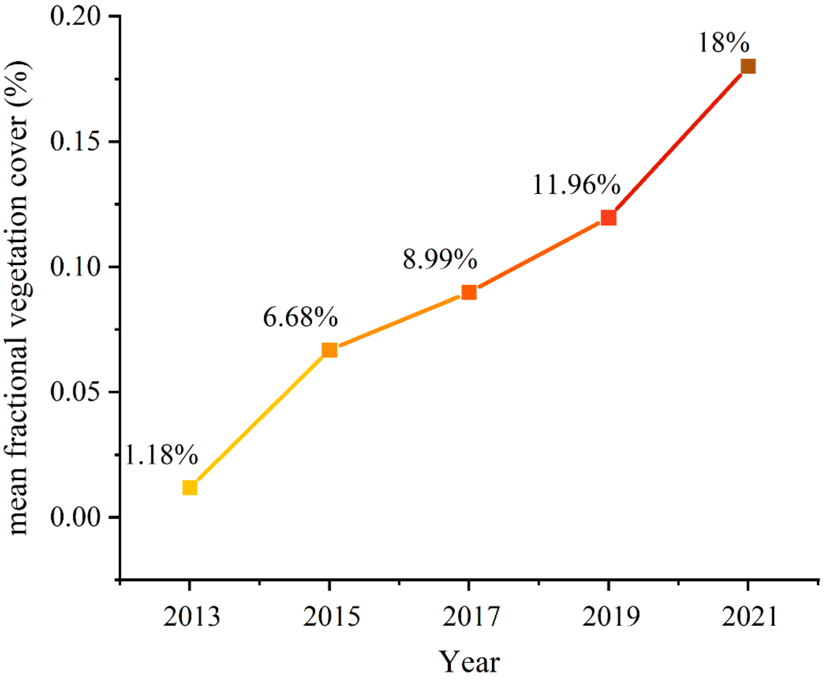

Fig.5 Interannual Variation Trend of Average FVC from 2013 to 2021

4.3 Comprehensive Assessment of Ecological Restoration Effectiveness

Integrating the spatial distribution patterns and temporal dynamics of FVC indicates that ecological restoration at the Maoming Open-pit Mine resulted in substantial improvements between 2013 and 2021. Overall, vegetation cover increased considerably throughout the mining area. During the study period, the mean FVC increased from 1.18% to 18.00%, representing an increase of 16.82 percentage points and demonstrating a sustained upward trend. Compared with the pre-restoration condition, characterized by extensive exposed surfaces and severely degraded vegetation, the study area exhibited progressive vegetation recovery following the implementation of ecological restoration measures.

Spatially, the vegetation cover pattern improved substantially. In 2013, vegetation was sparse and fragmented, with most of the study area consisting of exposed surfaces. By 2021, vegetation had become increasingly continuous along the margins of the mining area, while medium and high vegetation cover became concentrated within the principal restoration zones. Vegetation recovery progressively expanded from the peripheral areas toward the interior of the mining area, whereas areas with little or no vegetation became increasingly restricted to water bodies and a limited number of exposed rock surfaces. These spatial changes indicate the effective implementation of ecological restoration measures throughout the study area.

Temporally, the mean FVC increased continuously, rising more than fourteenfold during the study period. Areas without vegetation decreased markedly, whereas areas with medium and high vegetation cover expanded steadily. In addition, relatively stable and continuous vegetation communities gradually developed in several restored areas, indicating sustained improvements in vegetation conditions.

Overall, the ecological restoration project implemented at the Maoming Open-pit Mine between 2013 and 2021 substantially improved vegetation cover, vegetation cover structure, and spatial distribution patterns. These findings indicate that the primary restoration objectives of vegetation recovery and site rehabilitation were largely achieved. The restoration experience of the Maoming Open-pit Mine provides a useful reference for ecological restoration in other abandoned open-pit mining areas. Nevertheless, because vegetation recovery is still dominated by medium and high vegetation cover, while areas with very high vegetation cover remain limited, continued optimization of vegetation composition and long-term ecological management will be necessary to further enhance vegetation stability and ecological resilience.

V. CONCLUSION

Using the Maoming Open-pit Mine as the study area, this study analyzed Landsat series remote sensing imagery acquired between 2013 and 2021 and estimated FVC using the NDVI-based Pixel Dichotomy Model. Based on the spatiotemporal characteristics of vegetation cover before and after ecological restoration, the effectiveness of the restoration project was quantitatively evaluated. The main conclusions are summarized as follows.

First, ecological restoration substantially improved vegetation cover within the mining area. Before the implementation of the restoration project in 2013, long-term oil shale mining had resulted in extensive exposed surfaces and severe vegetation degradation, with a mean FVC of only 1.18%. By 2021, the mean FVC had increased to 18.00%, representing an increase of 16.82 percentage points over the study period. These results indicate that ecological restoration effectively promoted vegetation recovery and improved vegetation conditions throughout the mining area.

Second, vegetation cover exhibited distinct spatiotemporal evolution patterns. Spatially, vegetation recovery progressively expanded from the peripheral areas toward the central pit, accompanied by a transition from fragmented vegetation patches to increasingly continuous vegetation cover. During the early restoration stage, vegetation was primarily distributed along the mine margins and water diversion channels, whereas later restoration extended to the pit perimeter and spoil dumps. By 2021, medium and high vegetation cover had become concentrated in the eastern and northern restoration zones, while areas with little or no vegetation were mainly restricted to the steep southwestern slopes and a limited number of exposed rock waste piles. Temporally, the mean FVC increased continuously throughout the study period, with the most rapid increase occurring between 2019 and 2021, during which the mean FVC increased by an average of 3.02 percentage points per year.

Third, the structure of vegetation cover classes changed substantially during the restoration process. Before restoration, non-vegetated and bare soil areas accounted for 94.91% of the study area, whereas medium and high vegetation cover occupied only a small proportion. By 2021, the proportion of non-vegetated and bare soil areas had decreased to 60.53%, while low and medium vegetation cover increased markedly. High vegetation cover reached 14.65%, and areas with very high vegetation cover appeared locally. Overall, the vegetation cover structure shifted from predominantly exposed surfaces toward increasingly continuous vegetation cover, indicating progressive vegetation recovery.

Fourth, the combination of remote sensing data, FVC, and the NDVI-based Pixel Dichotomy Model provides an effective approach for quantitatively evaluating ecological restoration in mining areas. This method enables efficient long-term monitoring of vegetation dynamics and provides a practical framework for assessing restoration effectiveness, thereby supporting ecological management and future restoration planning.

Overall, the ecological restoration project implemented at the Maoming Open-pit Mine between 2013 and 2021 resulted in substantial improvements in vegetation cover and demonstrated clear progress in ecosystem recovery. The restoration practices and evaluation framework presented in this study may provide useful references for ecological restoration in other abandoned open-pit mining areas. Nevertheless, this study has several limitations. The analysis was limited to the period from 2013 to 2021 and relied primarily on FVC without incorporating additional indicators such as soil quality, hydrological conditions, or biodiversity. Furthermore, the analysis focused on the core mining area and did not evaluate ecological changes in the surrounding landscape. Future studies should extend the temporal coverage, integrate multi-source remote sensing and field observations, and develop a more comprehensive ecological assessment framework incorporating vegetation, soil, hydrology, and biodiversity to support long-term restoration planning and management.

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