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Research article

Policy support and the combination of artificial guidance with natural restoration can effectively restore the surface mine ecosystem in South China

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ABSTRACT

Assessing the effectiveness of ecological restoration policies in mining areas is vital for optimizing governmental investments and balancing financial expenditures with environmental recovery. Dongting Lake, China's second-largest freshwater lake, holds significant ecological importance in southern China, faces ecological challenges from legacy mines, yet the success of restoration efforts remains unclear. This study evaluated 170 abandoned surface mines (10 types) around Dongting Lake (2000–2023) using the Mine Landscape Restoration Index (MLRI) from remote sensing. Through MLRI time series analysis, four restoration types were identified, and their proportions and changes in MLRI values were statistically analyzed to assess the overall ecological restoration effect of the abandoned surface mines. The effectiveness of various restoration measures and policies was further compared to assess their practical impact. The effectiveness of ecological restoration policies was assessed, and the effectiveness of different restoration measures was compared to clarify the practical impacts of policies on the ecological restoration of surface mines and the applicability of restoration measures. Results indicate that 72.94 % of the mines have been significantly rehabilitated, with 105 achieving over 50 % restoration. The number of mine sites with ecologically significant restoration areas greater than 50 % is 15.48 % higher in artificially supported natural restoration than in artificially supported ecological reconstruction. Policy support has been instrumental in driving ecological recovery, with artificially supported natural restoration proving more effective than artificial ecological reconstruction. This study underscores the importance of policy support and the combination of artificial guidance with natural restoration in the ecological restoration of mining areas.

1. Introduction

Mineral resources are a vital component of natural resources and serve as the material foundation for socioeconomic development. However, while mining brings significant economic benefits, it also causes severe ecological problems, such as vegetation loss, landscape degradation, environmental pollution, intensified geological hazards, and biodiversity decline (Guan et al., 2017; Chen et al., 2022). Compared to other human activities like agriculture and urban expansion, mining exerts greater pressure on ecosystems due to its intense surface disturbance, wide-ranging pollution, and deep ecological disruption. As of 2022, mining activities had affected a global area of approximately 49.9 million km^2 (Tang and Werner, 2023), and by 2017, mining in China had cumulatively damaged more than 37,500 km^2 of land ((National Development, Reform, Commission, 2017). These figures highlight the urgent need for effective mine ecological restoration (Montanarella et al., 2018; Hobbs and Harris, 2001).

The success of mine restoration depends heavily on policy support and the implementation of appropriate restoration measures (Bonnail et al., 2023; Amores-Arrocha et al., 2023). Government investment influences restoration effectiveness through legislation, planning, regulation, and intervention strategies (Bonnail et al., 2023; Cao, 2007). In response to rising ecological pressures, numerous countries have enacted laws such as the Federal Mining Act and the Surface Mining Control

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and Reclamation Act. China has similarly implemented a series of policies, including the Land Reclamation Regulation and the Notice on Promoting Integrated Ecological Restoration. As of 2018, China had restored 9308 km^2 of mining land (Yang et al., 2021). However, restoration still lags behind actual needs due to a late start, weak foundations, and a significant backlog of degraded land. As of 2020, the national reclamation rate was approximately 57 %, and the annual treatment rate for newly damaged land was only about 40 %, with many sites showing signs of re-degradation post-restoration (Hu et al., 2022). Additionally, current assessments of policy effectiveness are limited by the small number and type of evaluated mining sites (Pan, 2022; Chen et al., 2016). Incorporating larger and more diverse datasets is key to identifying effective restoration strategies and evaluating policy outcomes.

The selection of suitable restoration measures remains a subject of ongoing debate (Hu, 2019). According to natural design theory, ecosystems may self-organize and recover under suitable environmental conditions given sufficient time (Peng, 2007; Van der Valk, 2009). Natural equilibrium theory posits that mild degradation can be reversed without intervention, whereas extreme cases require assistance. Human design theory, by contrast, emphasizes the role of active restoration through engineering and technological means (Middleton, 1999). In China, due to land scarcity and high population pressure, artificial restoration (particularly conversion to cropland and forestland) has long been prioritized (Zhang et al., 2018). More recently, the emergence of nature-based solutions has led to increasing attention to the feasibility and applicability of nature-based restoration in mining areas (Bai et al., 2020). The appropriate role of human intervention remains a central topic in restoration research (Amores-Arrocha et al., 2023; Canul et al., 2019; Mozdzer et al., 2021).

Long-term monitoring of mining ecosystems is an appropriate approach for identifying effective surface mine restoration measures and evaluating policy effectiveness. Tracking the ecological trajectories of mining areas over extended periods is crucial for assessing restoration outcomes (Arathi et al., 2019), as components of mining ecosystems—such as topography, soil, and biota—require substantial time to recover after mining operations cease (Poorter et al., 2021; Adame et al., 2018; Soria-Barreto et al., 2023). Evaluating the effectiveness of ecological restoration often relies on comparisons with either the pre-disturbance ecosystem or with similar undisturbed reference sites (Duriaux-Chavarria et al., 2021). However, due to the lack of unified management in the early stages of mining, historical ecological records are often missing, and identifying ecologically comparable reference areas can be challenging. Therefore, comparing current conditions with the long-term ecological history of the same mining sites offers a more feasible alternative. Traditional assessment methods, such as soil sampling and species inventory, can provide highly reliable data, but are difficult to sustain at large scales over long periods due to labor and funding constraints (Freitas et al., 2019; Lei et al., 2016; Zhou et al., 2020a). Remote sensing monitoring, supported by high-resolution imagery, has emerged as a valuable alternative (Song et al., 2020; Karan et al., 2016), and its sensitivity in detecting vegetation dynamics has been widely demonstrated (Rakotondrabe et al., 2018; Hu et al., 2022).

Dongting Lake, located in the Yangtze River Basin, is the second-largest freshwater lake in China and is surrounded by rich mineral resources. The frequent exploitation of these resources has caused a series of ecological and environmental problems, including land occupation, air pollution, and water contamination (Li, 2017). A large number of abandoned surface mines remain in need of ecological restoration. In the surrounding areas of Dongting Lake—such as Changde, Yiyang, and Changsha—there are 1921 abandoned surface mines, accounting for 55.26 % of the total (Gao et al., 2017). In recent years, mining activities have led to a substantial increase in the occupation of land types such as farmland, forest land, and water bodies, further highlighting the urgency of ecological restoration in mining areas. To protect and restore the ecosystem of the Dongting Lake Basin, the Chinese government released the Work Program for Ecological Restoration of Abandoned Surface Mines in the Yangtze River Economic Belt (hereinafter referred to as the "Program") in 2019, investing a large amount of funds to carry out targeted restoration work on abandoned surface mines around Dongting Lake. This program is one of the key policies introduced by China to comprehensively address the ecological and environmental issues of historically abandoned mines. The similar natural environments and policy contexts of the restored mines, along with a large number of restoration examples, provide solid data support for comparing the effectiveness of ecological restoration measures in these mines. Therefore, in this study, the area around Dongting Lake was selected as the study area with the main objectives:(a)Assessing the effectiveness of the ecological restoration policy implemented around Dongting Lake; (b) Determining what kinds of measures to ecological restoration is more effective for achieving the ecological restoration of abandoned surface mines around large freshwater lakes.

2. Materials and methods

2.1. Study area

The study area surrounds Dongting Lake in the middle reaches of the Yangtze River Basin. The region experiences a subtropical monsoon climate, averaging 1000–1800 mm annual precipitation and 15.7–17 °C. This study selected 170 abandoned surface mines within a 10 km buffer zone of Dongting Lake (Fig. 1). All mines are historically abandoned surface mines with unknown mining time, covering a total area of 4.68 $\times$ $10^6$$km^2$. Mining extents were derived from the 2017 China Mining Environment Remote Sensing Survey and field surveys across 11 districts and counties in Yueyang, Hunan Province. The types of mined minerals include 10 types of tuff for construction, clay for bricks and tiles, construction sand, granite for construction, limestone, limestone for construction, natural quartz sand, sandstone for construction, shale, shale for brick and tile (Table S1). Before the Program's launch, the 170 mines were undergoing natural recovery with minimal human intervention. After the release of the 2019 Program, each surface mine will carry out ecological recovery successively from 2019 to 2022. The recovery type of land use will include 3 types of forest and grassland, Cropland and Built-up and associated land (Table S1). This Program emphasizes that the management process should be based on ensuring the stability of the geological environment, restoring and upgrading the value of land resource utilization, combining vegetation restoration and mountain restoration to minimize bare ground and maximize greening.

2.2. Data resources

The remote sensing data used in this study were acquired at the GEE platform using 265 Landsat remote sensing images between June and September each year from 2000 to 2023. Specifically, Landsat 5 images were used for the years 2000–2011, Landsat 8 images for 2013–2021, and Landsat 9 images for 2022–2023. Remote sensing images taken by Landsat 7 in 2012 were not used due to gaps caused by satellite failure. Field photographs were taken between July 10, 2023 and July 15, 2023, and field interviews were conducted on July 11, 2023. Information on 170 surface mine types, time of recovery work and restoration measures is provided by the Technology Innovation Center for Ecological Protection and Restoration Engineering in Dongting Lake Basin of the Ministry of Providing Natural Resources.

2.3. Method

The data processing flow and methodology of this study are shown in Fig. 2. In the first step, the LST and EVI of 170 surface mines were calculated on Google Earth Engine (GEE) based on Landsat images taken from June to September each year from 2000 to 2023, and the MLRI time series of surface mines were constructed on the ArcGIS 10.2 platform. In the second step, the Mann-Kendall test, Sen's slope analysis, and

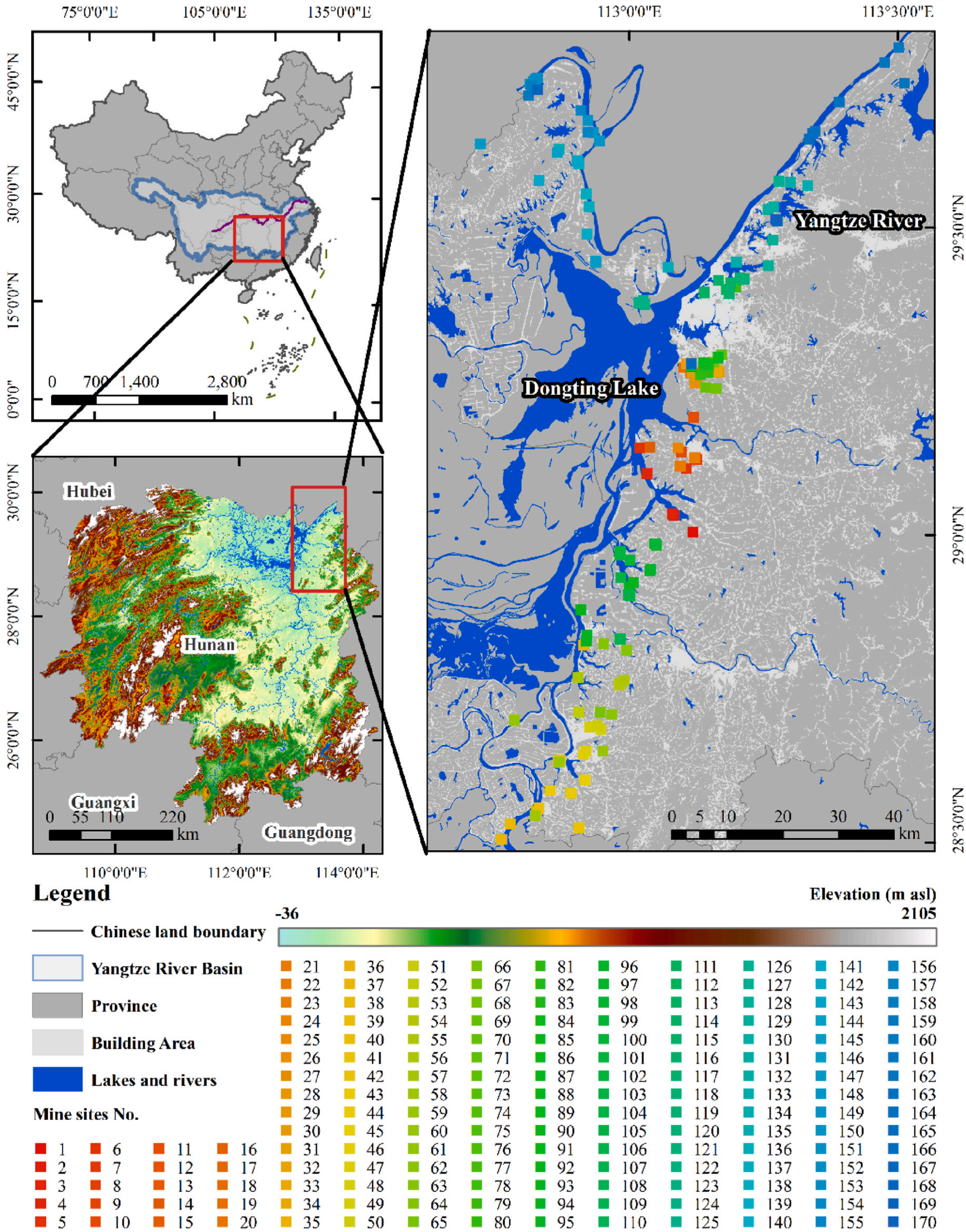

Fig. 1. Mines that were mapped and analyzed in this study.

Hurst exponent analysis were sequentially used for recovery identification and recovery type classification of the MLRI time series. Finally, the percentage of the area of different recovery types in each mine was determined, and the recovery effects of the 170 surface mines were analyzed in terms of three aspects: types of mines, land use after the completion of ecological restoration, and recovery measures. The effectiveness of policy inputs was assessed by monitoring the changes in MLRI values.

2.3.1. *Mine Landscape Restoration Index*

Vegetation is an important component of ecosystems (Overpeck and Breshears, 2021). Wang et al. (2020) demonstrated the reliability and superiority of the MLRI calculated on the basis of EVI and LST in the evaluation of ecological restoration effects and recovery identification of surface mines, which evaluates the growth of vegetation within each raster from the structural and functional perspectives and then portrays the overall state of the ecosystems in the mine area. EVI is very sensitive to the vegetation canopy structure, and when the ecosystem is disturbed,

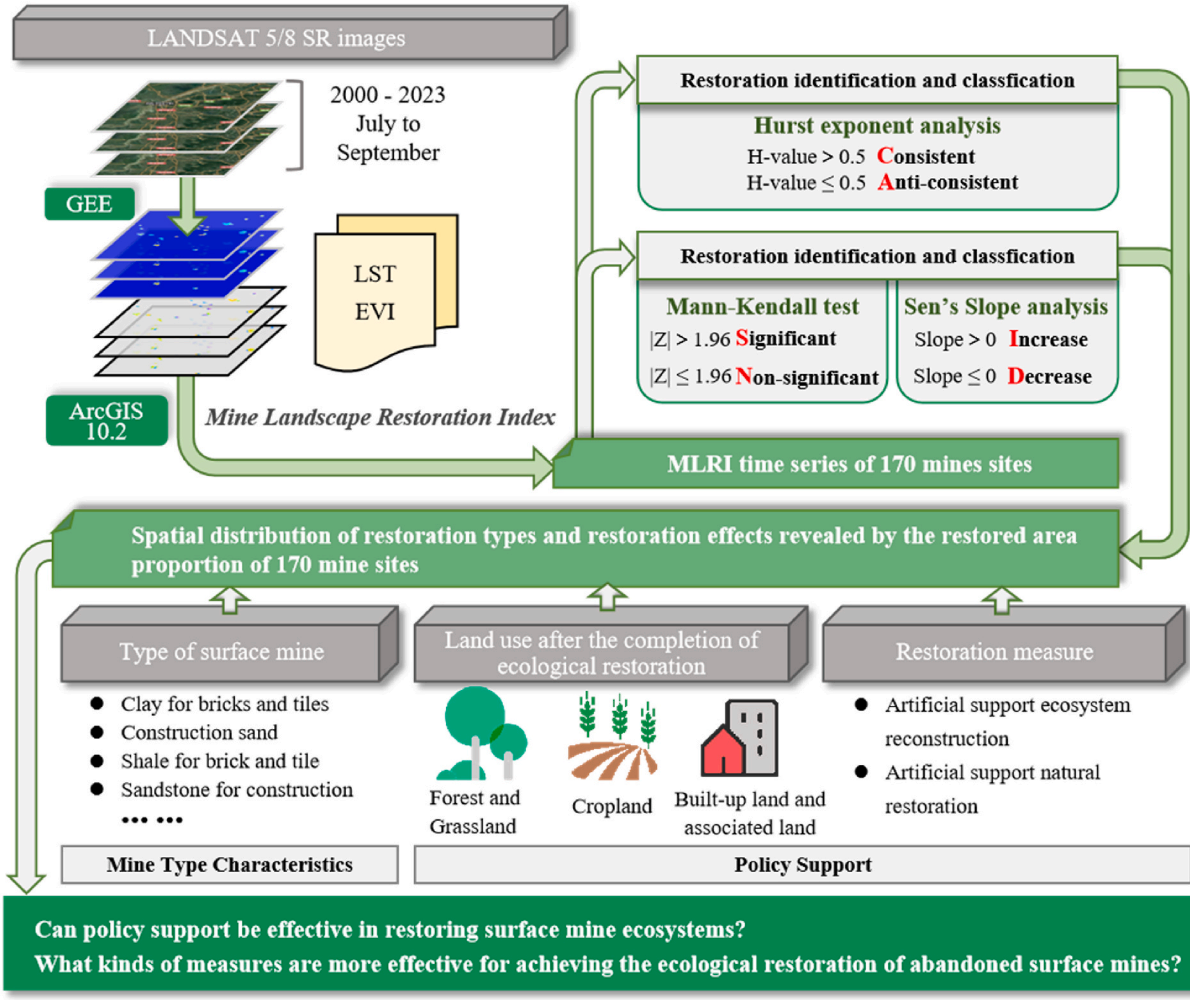

Fig. 2. Methodological flowchart.

the surface vegetation structure is severely disrupted and the EVI value decreases, and increases when the situation is reversed. Whereas the better the vegetation growth (Xie et al., 2019), the higher the evapotranspiration, the LST decreases with increasing evapotranspiration and rises when the situation is reversed. The minimum value of MLRI is 1. The larger the value of MLRI, the better the recovery effect, which is calculated as follows:

$$MLRI_{ij} = \frac{LST_{jmax}/EVI_{jmin}}{LST_{ij}/EVI_{ij}}$$

where: $MLRI_{ij}$ is the MLRI value of pixel j in year i; LST_{ij} and EVI_{ij} are the maximum composite LST and EVI values of pixel j in June to September in year i; LST_{jmax} and EVI_{jmin} are the maximum value of LST and minimum value of EVI of pixel j from 2000 to year i, respectively.

2.3.2. *Restoration effect monitoring results comparison*

To evaluate the reliability and consistency of MLRI in assessing the restoration effects of mining area ecosystems, commonly used ecological indices—such as the Enhanced Vegetation Index (EVI), Vegetation Condition Index (VCI), Normalized Difference Vegetation Index (NDVI), and Green Chlorophyll Index (GCI)—were employed for comparison. The corresponding calculation formulas are as follows:

$$EVI_{ij} = G \cdot \frac{NIR_{ij} - Red_{ij}}{NIR_{ij} + C_1 \cdot Red_{ij} - C_2 \cdot Blue_{ij} + L}$$

where: NIR_{ij} is the reflectance of the near infrared band for pixel j in year i; Red_{ij} is the reflectance of the red light band for pixel j in year i; $Blue_{ij}$ is the reflectance of the blue light band for pixel j in year i; G is the gain factor; C_1 and C_2 are the atmospheric correction coefficients; L is the soil adjustment parameter.

$$NDVI_{ij} = \frac{NIR_{ij} - Red_{ij}}{NIR_{ij} + Red_{ij}}$$

where: NIR_{ij} is the reflectance of the near infrared band for pixel j in year i; Red_{ij} is the reflectance of the red light band for pixel j in year i.

$$GCI_{ij} = \frac{NIR_{ij}}{Green_{ij}} - 1$$

where: NIR_{ij} is the reflectance of the near-infrared band for pixel j in year I; $Green_{ij}$ is the reflectance of the green light band for pixel j in year i.

$$VCI_{ij} = \frac{NDVI_{ij} - NDVI_{jmin}}{NDVI_{jmax} - NDVI_{jmin}} \times 100$$

where: $NDVI_{ij}$ is the NDVI value of the current period for pixel j in year i; $NDVI_{jmin}$ is the minimum NDVI value of pixel j from 2000 to year i, and $NDVI_{jmax}$ is the maximum NDVI value of pixel j from 2000 to year i, respectively.

2.3.3. *Restoration identification and classification*

MLRI is able to characterize the ecosystem status of the mining area, its temporal changes reflect recovery dynamics. Therefore, testing the trend and significance of MLRI change is the key to monitoring ecosystem recovery. The trends and significance of the MLRI series changes in 170 mining areas from 2000 to 2023 were firstly examined using Mann-Kendall test and Sen's slope analysis, and the time dependence of the changes was further examined using Hurst exponent analysis to identify the recovery process and the recovery areas, and to categorize the recovery types.

Mann-Kendall test can effectively distinguish whether a process is in a natural fluctuation or has a clear trend, and its test statistic Z can characterize the significance of the trend (Zhou et al., 2020b; Kendall, 1972). At $\alpha = 0.05$, $|Z| > 1.96$ denotes significant MLRI changes (Mann, 1945).

Sen's slope analysis robustly quantifies trend magnitude: positive slopes indicate increasing values, while negative slopes denote decreases. We applied this method to detect declines in MLRI.

Hurst exponent analysis can quantitatively characterize time series correlation, robustness to widely recognized (Hurst, 1951; Chang et al., 2023). The analysis outputs an h-value ranging from 0 to 1. When $h \leq 0.5$, the future trend of the time series is opposite to the past, while when $h > 0.5$, the future trend of the time series is consistent with the past. We used Sen's slope analysis to assess the long-term consistency of MLRI changes. We used these thresholds to classify MLRI temporal dependence.

According to the above steps to get the results 4 classification results can be obtained: (a) $|Z|>1.96$, slope >0, showing a significant increasing(SI) trend; (b) $|Z|\leq1.96$, slope>0, showing a non-significant increasing(NI) trend; (c) $|Z|\leq1.96$, slope<0, showing a non-significant decreasing(ND) trend; and (d) $|Z|>1.96$, slope >0, showing a significant decreasing(SD) trend. Where SI can be further categorized into 2 groups based on the value of h: (a1) $h > 0.5$, showing a significant consistent increasing (SCI) trend; (a2) $h \leq 0.5$, showing a significant anti-consistent increasing(SAI) trend. If the MLRI time series of the region shows a SI trend it means that there is a clear recovery process in the region. The recovery trend in the future of the region showing SCI trend is consistent. While the region showing SAI trend is not consistent, implying that there is a risk of degradation of the current recovery effect. There is no obvious recovery or disturbance in the areas showing NI and ND trends. Areas with SD trends are experiencing a steady decline in vegetation condition and are experiencing continued disturbance.

2.3.4. Restoration effect comparison

We used the Kruskal-Wallis test to compare whether there is a significant difference in the restoration effect due to different restoration measures. Kruskal-Wallis is a non-parametric test which does not require the data to show a normal distribution and is suitable for the data situation in this study. The mines in the study area carried out ecological restoration in 2019–2020, so this study counted the mean values of MLRI before restoration work was carried out (2000–2018) and after restoration work was carried out (2021, 2022, 2023) to compare the difference in restoration effects of different restoration measures.

2.3.5. Field survey and interviews

To gain a comprehensive understanding of ecological restoration efforts in the study area, we conducted a field survey and semi-structured interviews with key stakeholders. From July 10 to July 15, 2023, field surveys were conducted to observe restored mine sites, document ecological restoration progress, and collect photographic evidence. Simultaneously, in-depth interviews were performed with mining executives and government officials to explore their perspectives on restoration efforts, policy effectiveness, and implementation challenges (Table S2).

2.3.6. Classification of ecological restoration measures

To compare ecological restoration effects across different restoration measures, we classified the restoration measures accordingly. Based on the varying roles humans play in ecological restoration, and drawing upon previous studies such as Vaughn et al. (2010) and Bai et al. (2020), as well as China's Technical Specifications for Ecological Restoration of Mines (2022), we classified the ecological restoration approaches adopted in each mining site into two categories:(A) Artificially supported ecological reconstruction, which involves the cessation of human disturbance and the application of physical, chemical, or biological techniques to achieve ecological restoration through technical measures; (B) Artificially supported natural restoration, characterized by the cessation of human disturbance and relying solely on the ecosystem's self-regulatory capacity for restoration, without any human-derived inputs of materials or energy into the regional ecosystem.

3. Results

3.1. Abandoned surface mine around Dongting Lake gets recovered after policy implement

The proportion of restored area reflects the overall effectiveness of ecological restoration. Remote sensing monitoring results from 2000 to 2023 show that 105 out of 170 surface mines have restored a total area of more than 50 % of their total area. The structure and function of the ecosystems in these areas show significant restoration, indicating that the ecological restoration effect of abandoned surface mines near Dongting Lake is generally good.

To compare the recovery effectiveness of the mines as a whole and to facilitate analysis and management, the 170 surface mines were categorized into five groups based on the percentage of the area of the MLRI change type: (I) SCI$\geq$50 %, ND $=$ 0, SD $=$ 0; (II) SCI$<$50 %, ND $=$ 0, SD $=$ 0; (III) 0$<$ND $+$ SD $<$ 50 %; (IV) 50 %$\leq$ND $+$ SD $<$ 100 %; and (V) ND $+$ SD $=$ 100 %. Among them, the ecological restoration area of the mining areas in Groups I, II, and III was greater than 50 % of the total area of the mining area, with 52, 20, and 33 mines respectively. In contrast, the restoration area of Groups IV and V was less than 50 % and did not show effective restoration, with 19 and 46 mines respectively.

After restoration, differences in restoration outcomes were found to be associated with variations in mine type and post-restoration land use (Fig. 3, Table S1). Among the types of mines with more than five in number, there are 51 surface mines (63.75 %) with clay for bricks and tiles belonging to types I, II and III, and 28 (65.12 %) with construction sand, which have a better restoration effect. The restoration of shale for bricks and tiles is poorer, and there are only 11 surface mines (37.93 %) belonging to categories I to III. The best restoration results were seen in the mines where the land use after restoration was forest and grassland, with all 61 mines demonstrating effective restoration (71.43 %). The restoration effect of 42 mines (63.93 %) where the land use after restoration is arable land is good, which is close to the former. Only two of the mines (11.11 %) with land use for construction after ecological restoration showed significant restoration.

3.2. Abandoned surface mines around Dongting Lake have been restored through targeted rehabilitation policies

The ecological conditions of surface mines in the study area improved following the implementation of restoration projects in 2019–2020. The logarithmic values of the mean MLRI values for 2000–2018 before the restoration measures were compared to the mean MLRI values for 2021, 2022, and 2023 after the restoration measures. Ratios greater than 1 represent an increase in the mean MLRI value after the Program was implemented, less than 1 represent a decrease, and equal to 1 represent no change (Fig. 4). Out of the 170 surface mines, 124 (72.94 %) saw an increase in MLRI values after restoration. We further analyzed the mean MLRI values in the four categories of change areas—SI, NI, ND, and SD—from 2000 to 2023, and fitted them to form a curve (Figure S1–170). There was a significant increase in the SI regional means after ecological restoration work, with some regions showing

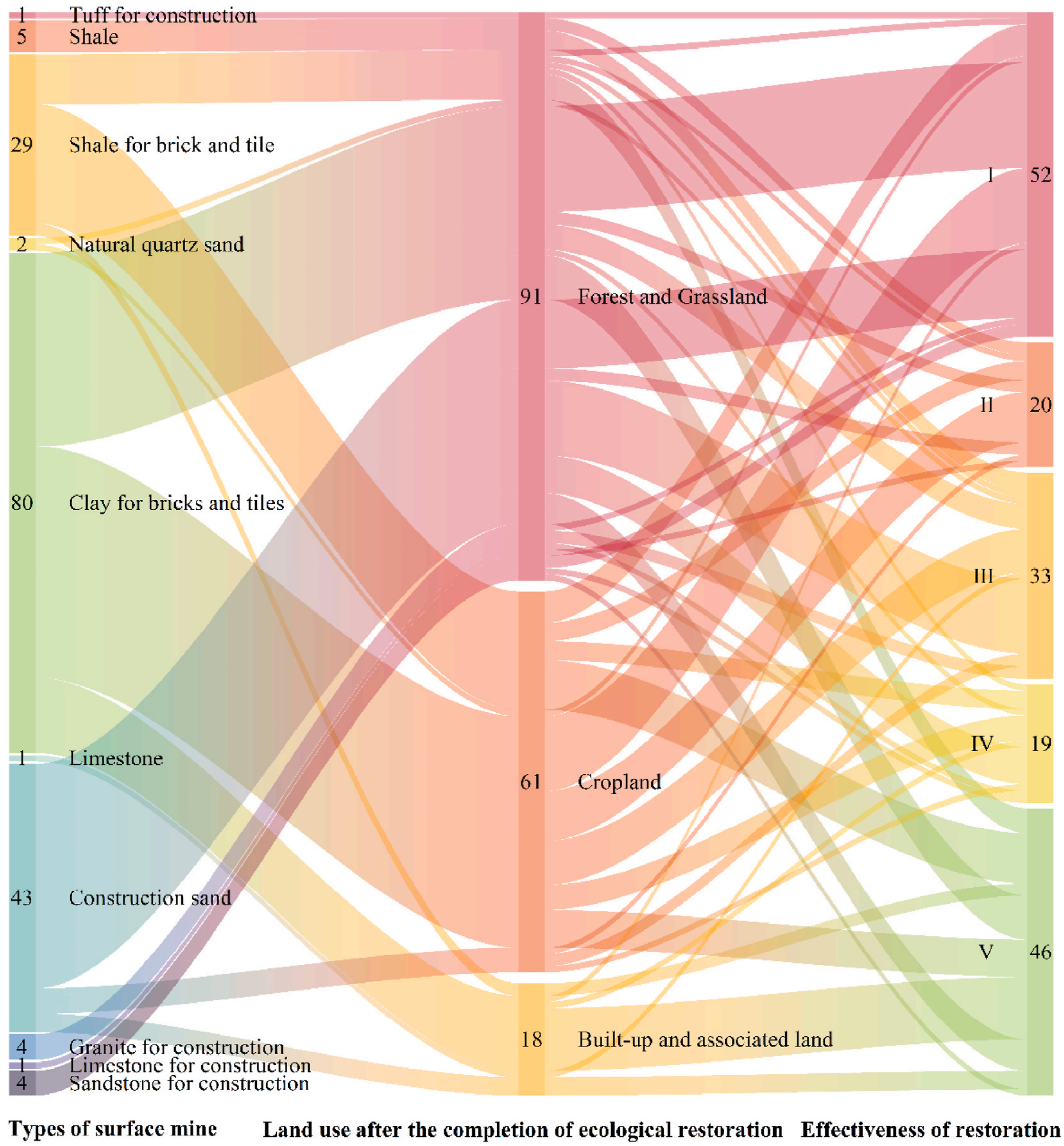

Fig. 3. The Correspondence Between Surface Mine Types, Land Use After Ecological Restoration, and the Effectiveness of Restoration in the Study Area (Arabic numerals represent the number of mines; I ~ V correspond to the five groups mentioned in Section 3.1).

historical peaks in 2021–2023 and even continuing increases. NI averages have risen slightly since the implementation of the recovery effort. The downward trend of the mean MLRI values in the ND and SD regions was not significantly suppressed, indicating that the changes in the mean MLRI values in these regions were not significantly affected by the restoration inputs (Fig. 5). Fig. 6 shows the spatial distribution results of restoration types in representative mining areas of I to V. Additionally, the fluctuation patterns of the mean MLRI curves did not exhibit significant similarities by mineral type or geographic distribution.

3.3. *Artificially supported natural restoration can be more effective in improving the ecological environment of abandoned surface mines*

In the study area, ecological restoration measures with higher artificial inputs dominate, with 69 surface mines adopting artificially supported natural restoration, covering a total area of about 177.802 × 104 km^2; and 101 surface mines adopting artificially supported ecological reconstruction, covering a total area of about 290.667 × 104 km^2 (Table S1).

Artificially supported natural restoration can be more effective in improving the ecological environment of abandoned surface mines in the study area. Statistics on the restoration area of 162 surface mines of 6 types with both A and B restoration measures (Fig. 6, Table S1) show that the restoration of clay for brick and tile (80 mines), construction sand (43 mines), granite for construction (4 mines), sandstone for construction (4 mines), and shale for brick and tile (29 mines) is more effective in the implementation of the restoration measures of type A, and the opposite is observed in the case of the shale surface mines (2 mines). Statistics on the logarithmic change of the 3-year average value of MLRI before and after the ecological restoration work was carried out showed that the minimum, maximum and suspension of the MLRI of surface mines using Category A restoration measures showed a more pronounced increase, and the effect of ecosystem restoration was more significant (Fig. 6, Table S3).

4. Discussion

4.1. *Government support and ecological restoration of surface mines*

Long-term monitoring of 170 surface mines confirms the

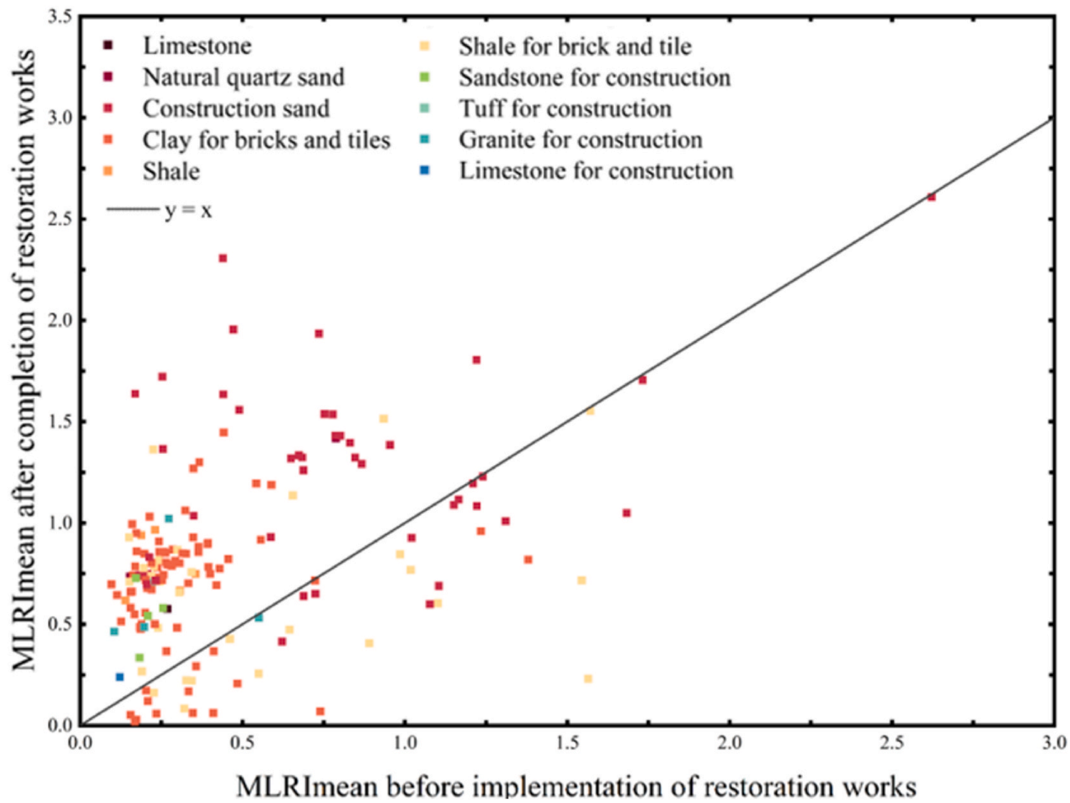

Fig. 4. Ratio of MLRI mean values before and after ecological restoration in the study area.

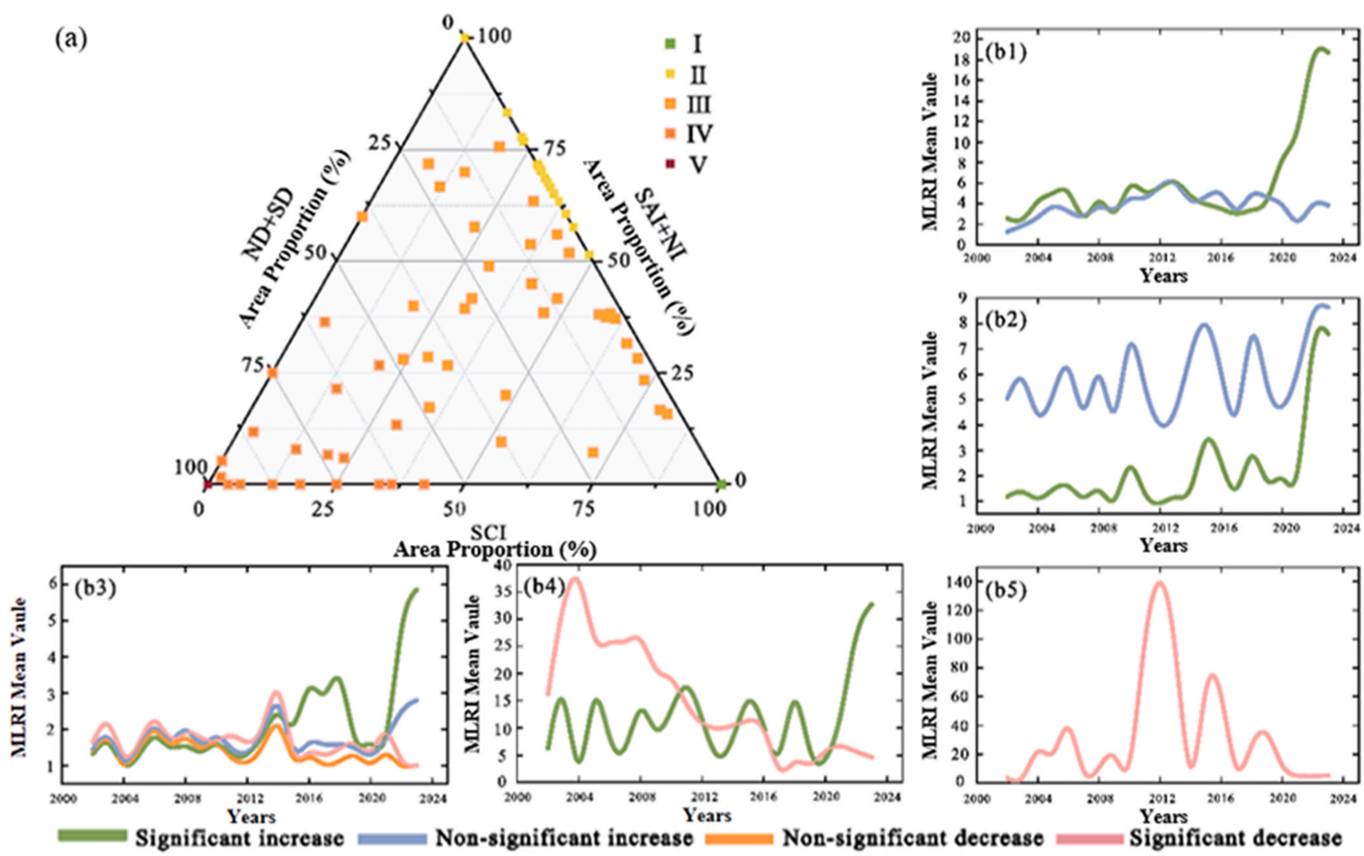

Fig. 5. MLRI changes in 170 surface mines (2000–2023). (a) Restoration classification percentages for groups I–V; (b1) MLRI change curve for group I representative mine (no. 157); (b2) MLRI change curve for group II representative mine (no. 63); (b3) MLRI change curve for group III representative mine (no. 1); (b4) MLRI change curve for group IV representative mine (no. 41); (b5) MLRI change curve for group V representative mine (no. 121).

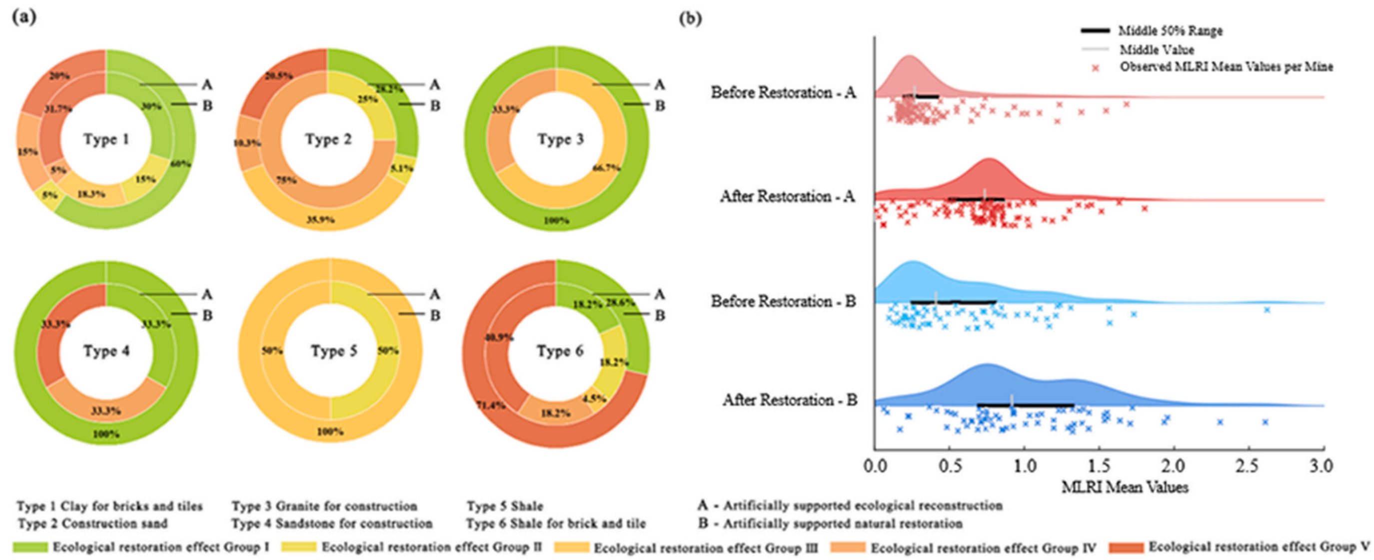

Fig. 6. Restoration effects of different measures in surface mines. (a) Ecological restoration effectiveness by mine type under two measures; (b) MLRI mean values before and after restoration by mine type.

effectiveness of government-led ecological restoration. After the implementation of the program, abandoned surface mines of clay for bricks and tiles, sandstone for construction, granite for construction, limestone for construction, natural quartz sand, sandstone for construction, shale, and tuff for construction all showed better ecological restoration results three years after the ecological restoration work was carried out.

A major concern in ecological restoration is balancing government inputs with associated costs. Government involvement—through legislation, policy, land-use planning, public awareness, and research—shapes all aspects of restoration and influences outcomes (Roberto et al., 2021). Aligning restoration efforts with strategic planning, selecting appropriate measures, improving economic returns can help reduce government spending and resource use.

Uniform development of the plan will avoid loss of resources due to changes in the land use plan. Our field investigation revealed that the Xinyue surface mine, which was initially restored to forest and grassland, was later repurposed as construction land (Fig. 7). This mismatch arose because the Yueyang City Territorial Spatial Master Plan covers the period from 2021 to 2035, while the Work Program for Ecological Rehabilitation of Abandoned Surface Mines in the Yangtze River Economic Belt was implemented between 2019 and 2020. Such temporal inconsistencies between policy frameworks and land-use planning should be addressed to avoid inefficient resource allocation (Chen et al., 2022b; Couix and Gonzalo-Turpin, 2015).

Selecting appropriate restoration methods and enhancing the economic productivity of restoration can reduce costs and improve sustainability (Shi et al., 2025; Xu et al., 2023). This study examined the effectiveness of different restoration measures for surface mines. Artificially supported natural restoration is more cost-effective than ecological reconstruction, and selecting suitable methods can lower investment requirements (Brancalion et al., 2020; Andres et al., 2024). Efficient use of by-products, such as stone generated during surface mine restoration, can enhance the economic returns of the restoration process (Thomas et al., 2024). In 2019, China's Ministry of Natural Resources of China issued the Opinions of the Ministry of Natural Resources on Exploring the Use of Market-based Approaches to Promote Mine Ecological Rehabilitation, advocating for a scientifically governed, market-driven restoration mechanism to strengthen national land rehabilitation capacity. Some study sites adopted this market-based model. Although its direct impact on ecological efforts was not confirmed, field interviews indicated that it provided valuable economic support for restoration efforts.

4.2. *Differences in ecological restoration of surface mines resulting from land use types and mine characteristics*

Ecosystem complexity and biomass are positively associated with restoration success. Forest–grassland ecosystems, characterized by higher species diversity within shared niches, exhibit greater stability and complexity. As a result, they generally achieve better functional and structural recovery than agricultural or construction lands under similar restoration periods, consistent with previous studies (Yang, 2018; Chen et al., 2022a). However, our results show no statistically significant difference in restoration efforts between forest-grassland areas and croplands, diverging from widely accepted findings. This discrepancy may be explained by factors such as the relatively short restoration timeframe in the study area and the presence of abandoned cropland. Prior studies suggest that secondary succession after forest and grassland degradation often requires extended periods to reach ecological stability (Poorter et al., 2021). Since only three years have passed since restoration, these ecosystems may not yet have stabilized, allowing room for further recovery. Additionally, field surveys revealed that some croplands were left fallow rather than cultivated, potentially contributing to the minimal differences observed. This interpretation is supported by the MLRI curve, which has yet to show stable fluctuations within a defined range.

The type and location of a surface mine significantly influence restoration efforts. Mines with minimal topographical disturbance, limited topsoil removal, and good accessibility generally achieve better recovery. Key characteristics—such as type, size, and extraction method—shape ecological challenges and affect restoration efficiency (Dong et al., 2019). Restoration ecology holds that more severe degradation requires longer recovery, a principle supported by our findings. Clay mines for brick and tile production and construction sand mines, which involve less topsoil disruption, showed better recovery within the same timeframe. Unlike other surface mines requiring extensive mountain excavation, clay mines typically involve localized excavation within a confined pit, and certain construction sand mines involve limited land alteration. In these cases, land compression and occupation rather than excavation represent the main ecological disturbances. These mines face shorter recovery periods due to their lower degradation levels. Our findings also highlight the critical role of topsoil, consistent with previous studies (Ngugi et al., 2020; Rovere and Calabrese, 2011). Clay

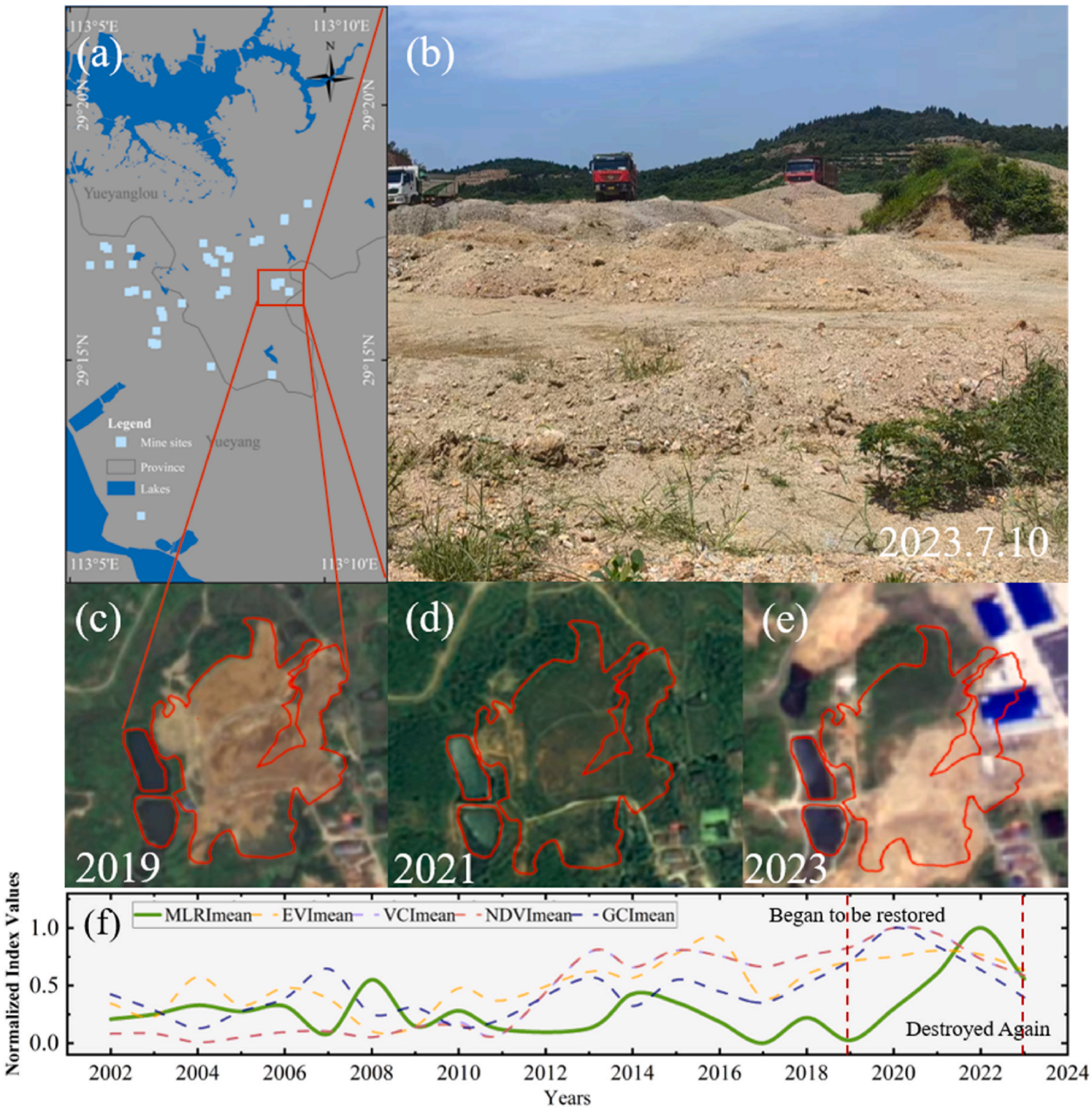

Fig. 7. Land Cover Changes and corresponding Multiple Monitoring Indices with MLRI Comparison in Xinyue Surface Mine Over Time. (a) Location of Xinyue Surface Mine; (b) Field Photo of Xinyue Mine (July 10, 2023), which shows degradation after restoration; (c) Remote Sensing Image Before Ecological Restoration (2019); (d) Remote Sensing Image After Ecological Restoration (2021), which shows vegetation has recovered; (e) Remote Sensing Image After Redevelopment for Construction Land (2023); and (f) Multiple Monitoring Indices with MLRI Comparison in Xinyue Surface Mine Over Time.

mines for bricks and tiles are usually found in flat, accessible areas such as villages and farmland, while construction sand mines are located along rivers or lakes, where access to materials and labor is easier. Additionally, COVID-19 control measures in 2019–2020, including transport and workforce restrictions, may have exacerbated geographic disparities in restoration efficiency.

4.3. Ecological restoration measures and surface mine restoration effects

In subtropical monsoon climate regions, non-metallic surface mines can achieve better ecological restoration by appropriately controlling the intensity of artificial inputs and conducting artificially guided natural restoration. A significant difference was observed in average MLRI values between the two approaches, with higher values recorded in areas using the artificially guided natural restoration—consistent with previous findings (Zhang et al., 2017; Hu et al., 2014). The Dongting Lake region's abundant rainfall, strong sunlight, and simultaneous heat and precipitation create favorable conditions for vegetation growth. Most study sites in this study were small-scale mines with minimal disturbance. Their irregular boundaries and compact size allowed surrounding ecosystems to support internal recovery (Bai et al., 2018), contributing to the success of guided natural restoration. In contrast, other studies conducted in arid and semi-arid regions found that higher artificial input yields better short-term efforts (<3 years) due to limited natural recovery capacity (Martínez-Ruiz et al., 2007; Liu et al., 2023). The relatively harsh natural conditions in these regions limit vegetation growth. The conclusions of this study provide more references for the selection of ecological restoration measures for abandoned surface mines.

4.4. MLRI sensitivity and policy effectiveness evaluation

MLRI has demonstrated high reliability and sensitivity in monitoring ecological restoration effects in mining areas. The Xinyue Surface Mine was selected as a case study due to its well-documented land cover changes, providing an optimal context for evaluating MLRI's performance. The results indicate that MLRI closely aligns with observed changes in remote sensing imagery, confirming its reliability (Fig. 7). Specifically, the temporal trends of MLRI were consistent with those of EVI, VCI, NDVI, and GCI, collectively reflecting a positive recovery trend in the Xinyue mining area. We systematically compared the coefficients of variation (CV) of various ecological indices before the implementation of ecological restoration, along with their relative changes before and after restoration. The results show that MLRI exhibited moderate variability prior to restoration (CV = 0.571) and experienced a substantial relative increase of 113.9 % after restoration. Compared with conventional vegetation indices (e.g., NDVI, VCI), the MLRI exhibits both high relative change (113.9 %) and moderate pre-restoration variability (CV = 0.57), suggesting that it is not only sensitive to ecological restoration efforts but also robust against short-term environmental noise (Table 1). These findings highlight the superiority of MLRI in evaluating the effectiveness of ecological restoration policies.

The comparison of multi-index monitoring results highlights the superiority of MLRI in long-term ecosystem restoration of mining areas. MLRI establishes a "structure-function" collaborative assessment framework by EVI and LST data (Guan et al., 2023; Wang et al., 2023). Specifically, EVI quantifies vegetation canopy structure, reflecting the physical characteristics of vegetation recovery during ecological restoration, while LST represents the surface thermal environment, indirectly indicating the influence of vegetation evapotranspiration on energy balance. The MLRI algorithm uses long-term maximum LST and minimum EVI as benchmarks, standardizing interannual data to highlight the synergistic trend of increasing EVI and decreasing LST during restoration. Compared to traditional vegetation indices such as NDVI and EVI, MLRI not only captures vegetation cover changes but also identifies improvements in surface moisture and thermal conditions through LST responses, demonstrating superior sensitivity.

A fundamental principle of ecosystem restoration is reestablishing the dynamic balance between structure and function (Xu et al., 2025). The synergy between these two aspects is a key driver of comprehensive ecosystem recovery. By integrating EVI and LST, MLRI unifies vegetation structure restoration and ecological function improvement, addressing the limitations of single-indicator evaluations such as EVI, VCI, NDVI, and GCI. MLRI's dual capability—high sensitivity and a comprehensive evaluation of vegetation structure and function—positions it as an invaluable tool for monitoring and assessing ecological restoration in mining areas. The strong performance observed in this study highlights its reliability and potential to guide data-driven decision-making and improve restoration strategies.4.5 Limitations and Future Work.

In this study, we evaluated the ecological restoration efforts of the Work Program for Ecological Restoration of Abandoned Surface Mines in the Yangtze River Economic Belt (2019–2020) by monitoring vegetation growth across 170 surface mines near Dongting Lake from 2000 to 2023. We further compared the restoration effectiveness of different ecological restoration measures. However, several limitations remain due to constraints related to recovery time and data availability. First, although the overall number of surface mines assessed is relatively high, the sample size for certain mineral types is limited due to data constraints in the study area. Future research could focus on specific mineral types to explore restoration effects in greater detail. Second, this study relied on Landsat remote sensing data with a spatial resolution of 30 × 30 m m, which provides only a general overview of vegetation recovery in small surface mines. This resolution is insufficient for assessing the effectiveness of specific restoration measures within individual mine sites. Future studies could incorporate higher-resolution remote sensing data to enable more detailed comparisons of restoration performance across different restoration strategies within the same mine area. Due to data limitations, this study did not achieve specific quantification of policy inputs, but this shortcoming can be supplemented in future research.

Table 1
Sensitivity comparison of ecological indices to restoration.

	CV	Relative Change (%)
MLRI	0.57	113.9
EVI	0.58	64.5
VCI	1.02	173.7
NDVI	1.03	175.1
GCI	0.49	124.6

5. Conclusions

This study monitored vegetation growth in 170 abandoned surface mines around Dongting Lake from 2000 to 2023. We assessed the ecological restoration of 170 abandoned surface mines after the implementation of the Work Program for Ecological Rehabilitation of Abandoned Surface Mines in the Yangtze River Economic Belt by identifying the recovery area and process. This study compared the effects of different ecological restoration measures, exploring the role of humans in ecological restoration and the impact of policy support. Overall, the ecological recovery of abandoned surface mines near Dongting Lake was found to be favorable, with the most significant recovery observed in areas restored to forest-grassland land use. Government support plays an essential and positive role in the ecological restoration of surface mines. The artificially guided natural restoration can better realize the ecological restoration of non-metallic surface mines in the region of subtropical monsoon climate in areas with simultaneous rain and heat. The conclusions of this study have reference value in the formulation of ecological restoration guidelines and measure selection for non-metallic mines near subtropical freshwater lakes. They provide a rich case for the practical application of ecological restoration theory.

CRediT authorship contribution statement

Yi Peng: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Le Xia:** Supervision, Investigation, Funding acquisition. **Yunxuan Liu:** Writing – review & editing, Methodology. **Ruojun Yang:** Supervision, Investigation, Funding acquisition. **Chanyu Zheng:** Supervision, Investigation, Funding acquisition. **Miaomiao Xie:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126579.

Data availability

The authors do not have permission to share data.

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