# Impacts of Climate and Mining Activities on Vegetation in Open-pit Mining Areas of Desertified Grasslands: Postprint

**Authors:** Wang Shiwei, Zhang Haobin, Guo Wenbing, Ma Chao

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## Abstract

Studying vegetation damage and reclamation status in open-pit mining pits and waste dumps can provide an ecological basis for diagnosing vegetation damage, assessing natural recovery, and evaluating artificial restoration in mining areas. Based on Sentinel-2 data, non-red-edge vegetation indices (NDVI, EVI) and red-edge vegetation indices (RENDVI, MSR_{RE}, CIre, TCARI) were calculated as ecological restoration evaluation indicators. Using regression analysis, trend analysis, and correlation analysis methods, the impacts of mining activities and climate change on vegetation growth in five open-pit mines (Wulanhada Open-pit Mine, Jingwei Open-pit Mine, Wujiata Open-pit Mine, Langwoqu Open-pit Mine, and Hongshengyuan Open-pit Mine) from 2018 to 2023 were analyzed to obtain the spatiotemporal variation patterns of vegetation in mining pits, waste dumps, and buffer zones of the mining areas. The results show that: (1) The vegetation damage in the mining pit of Hongshengyuan Open-pit Mine was the most severe (fitting slope k=-0.2996), but its waste dump had the best artificial restoration effect (fitting slope k=0.1364). (2) Comparing the 5 km buffer zones of the five open-pit coal mines, it was found that the pixel-by-pixel RENDVI change trends were mainly degradation, with degraded areas accounting for more than 50%. (3) In desertified grassland areas, vegetation NDVI changes were less affected by precipitation than by temperature. Open-pit mining exacerbates the degradation of desertified grassland vegetation, and artificial restoration of waste dumps has significant effects on improving regional vegetation growth conditions.

## Full Text

# Effects of Climate and Mining Activities on Vegetation in Open-Pit Mining Areas of Desertified Grasslands

**WANG Shiwei**[1], **ZHANG Haobin**[1], **GUO Wenbing**[2], **MA Chao**[1],[3],[4]

[1]School of Surveying and Land Information Engineering, Henan Polytechnic University, Jiaozuo 454003, Henan, China
[2]School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, Henan, China
[3]Key Laboratory of Spatio-Temporal Information and Ecological Restoration of Mines (MNR), Henan Polytechnic University, Jiaozuo 454003, Henan, China
[4]Research Center of Arable Land Protection and Urban-Rural Quality Development in Yellow River Basin, Henan Polytechnic University, Jiaozuo 454003, Henan, China

### Abstract

Investigating vegetation damage and reclamation status in mining pits and waste dumps of open-pit mines provides an ecological basis for diagnosing vegetation damage and evaluating natural recovery and artificial restoration in mining areas. Based on Sentinel-2 data, we calculated non-red-edge vegetation indices (NDVI and EVI) and red-edge vegetation indices (RENDVI, MSR_{RE}, CI_{{{red}}_{{edge}}}, and TCARI) as ecological restoration evaluation indicators. Using regression analysis, trend analysis, and correlation analysis, we examined the impacts of mining activities and climate on vegetation growth in five open-pit mines (Wulanhada, Jingwei, Wujiata, Langwoqu, and Hongshengyuan) from 2018 to 2021, revealing spatiotemporal patterns of vegetation change in mining pits, waste dumps, and buffer zones. The results show: (1) The Hongshengyuan open-pit mine exhibited the most severe vegetation damage in its mining pit (fitting slope k = -0.2996), yet achieved the best artificial restoration effect in its waste dump (fitting slope k = 0.1364). (2) Pixel-by-pixel RENDVI trend analysis in 5 km buffer zones around the five mines revealed degradation as the dominant pattern, with degraded areas exceeding 50% in all cases. (3) In desertified grassland regions, vegetation is less affected by precipitation than by temperature. Open-pit mining exacerbates vegetation degradation in desertified grasslands, while artificial restoration of waste dumps effectively improves regional vegetation growth conditions.

**Keywords:** desertified grassland; Shendong mining area; open-pit mining; waste dump; vegetation index; ecological restoration

## 1. Introduction

Desertified grassland regions represent one of Earth’ s most ecologically fragile zones, where ecosystem stability and biodiversity are highly susceptible to human disturbance. With rapid global economic development, demand for mineral resources has surged, intensifying open-pit mining activities. However, open-pit mining not only directly destroys surface vegetation and soil structure but also indirectly impacts surrounding environments through dust and tailings accumulation, leading to further ecosystem degradation. Therefore, assessing the extent of vegetation damage caused by open-pit mining and developing effective ecological restoration strategies have become urgent challenges.

Open-pit mining areas are extensive and difficult to access, making remote sensing index methods highly effective for monitoring and evaluating ecological restoration. Research on mining area restoration monitoring using remote sensing has evolved through three stages. The first stage (pre-2010) primarily used single indicators to monitor surface vegetation recovery in underground mines. For example, Hu Zhenqi et al. used NDVI to monitor vegetation cover changes in the Shenfu mining area, while Wu Lixin et al. and Ma Baodong et al. developed improved remote sensing ecological indices based on moving window models. The second stage (2010-2020) adopted multi-source data and multi-indicator approaches, expanding from underground to open-pit mines. Karan et al. found significant reclamation effects in the Jharia coal mine area, while Zhang et al. observed improved vegetation restoration in the Pingshuo open-pit mine. Erener evaluated vegetation health in reclaimed areas of the Seyitömer open-pit coal mine. The third stage (post-2020) has seen the development of comprehensive indicator analysis methods, such as the Normalized Difference Environmental Vegetation Index for grassland mining areas and pressure-response models for analyzing long-term environmental changes.

Current research on mining area vegetation damage primarily relies on NDVI, without utilizing highly sensitive red-edge indices. Studies also suffer from small sample sizes, often focusing on single open-pit mines and lacking generalizable patterns, with limited analysis of climate change impacts on surrounding vegetation. To address these gaps and solve the problems of diagnosing vegetation damage and evaluating natural recovery versus artificial restoration, this study employs a multi-region, multi-angle, and multi-vegetation-index approach based on Sentinel-2 remote sensing data. We diagnose vegetation damage caused by open-pit mining in desertified grasslands, assess waste dump restoration effectiveness, and analyze the influence of climate change. This research aims to deepen understanding of vegetation damage mechanisms in desertified grassland open-pit mines, promote regional sustainable development and long-term ecosystem stability, and provide scientific basis and decision-making support for ecological restoration.

## 1.1 Study Area Overview

This study focuses on the loess-aeolian sand region in the middle and upper reaches of the Yellow River, selecting five major open-pit coal mines in the Kuye River basin of the Shendong mining area: Wulanhada, Jingwei, Wujiata, Langwoqu, and Hongshengyuan. Given the maximum spatial span of 92.50 km and elevation differences, we selected southern and northern comparison areas (Figure 1) as background zones for natural variation based on the distribution characteristics of the mines to minimize external factor impacts.

The Shendong mining area in the semi-arid desertified grassland belongs to the Shendong coal base, spanning Shenmu City and Fugu County in Shaanxi Province, and Yijinhuoluo Banner and Zhungeer Banner in Inner Mongolia Autonomous Region. Located in the transition zone between the Loess Plateau hilly-gully region and the Mu Us Desert in the middle and upper Yellow River, the area has low vegetation coverage, arid climate, poor disturbance resistance, and extremely fragile ecological conditions. The region experiences a temperate continental monsoon climate with distinct seasons, cold winters, hot summers, dry and windy springs/winters, and concentrated summer rainstorms. Annual precipitation ranges from 370-490 mm with extreme unevenness. Soils are primarily loess, loess-like silt, and aeolian sand, frequently affected by wind and water erosion. Native vegetation is simple, dominated by dry grassland, deciduous broadleaf shrub, and psammophytic communities.

## 1.2 Data Sources

**Remote Sensing Data:** Multi-spectral data from Sentinel-2A/B satellites were obtained from the Copernicus Data Space (https://dataspace.copernicus.eu). The Sentinel-2 sensor includes 13 spectral bands from visible light to shortwave infrared, offering high spatial resolution, short revisit cycles, multiple bands, and narrow bandwidths. We collected time series data from 2018-2021, selecting images from July-August during peak vegetation growth. Due to heavy cloud cover, Wulanhada mine lacked data for July-August 2018.

**Meteorological Data:** Monthly average temperature and total precipitation raster data at 1 km resolution were obtained from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn/zh-hans/). Given the large study area, meteorological data covered Shenmu City, Fugu County, Yijinhuoluo Banner, and Zhungeer Banner.

Basic information for the five mines is summarized in Table 1, and remote sensing image details are provided in Table 2.

## 1.3 Methods

**1.3.1 Data Preprocessing** Sentinel-2 satellite data preprocessing included atmospheric correction, resampling, band fusion, and surface reflectance restoration. To obtain mining pit and waste dump boundaries, we used the multi-scale segmentation tool in eCognition® on fused imagery, exported the boundaries, and performed mean and maximum value compositing of vegetation index data in ArcGIS® for time series and buffer zone trend analysis.

**1.3.2 Vegetation Indices** From over 20 published vegetation index models, we selected six indices: Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Red Edge Normalized Difference Vegetation Index (RENDVI), Modified Red Edge Simple Ratio (MSR_{RE}), Chlorophyll Index red edge (CI_{{{red}}_{{edge}}}), and Transformed Chlorophyll Absorption in Reflectance Index (TCARI). Since Sentinel-2A/B band center wavelengths don' t perfectly match those of selected vegetation indices, we used adjacent bands: Band 4 (665 nm) for red, Band 5 (705 nm) for red edge 1, Band 6 (740 nm) for red edge 2, Band 7 (783 nm) for red edge 3, Band 8 (842 nm) for near-infrared, and Band 8A (865 nm) for narrow near-infrared. Calculation equations and corresponding bands are shown in Table 3.

**1.3.3 Linear Fitting** To analyze temporal changes in open-pit mines and waste dumps, we performed linear fitting on vegetation index curves. The equation slope reflects vegetation index trends, enabling analysis of vegetation damage and reclamation status:

$$y = kx_i + b$$

where $k$ is the slope, $b$ is the constant term, $x_i$ is year $i$, and $y$ is the vegetation index value.

The coefficient of determination ($R^2$) assesses model fit quality:

$$R^2 = \frac{SSR}{SST} = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2}$$

where $SSR$ is regression sum of squares, $SST$ is total sum of squares, $\hat{y}_i$ is predicted value, and $\bar{y}$ is mean value. $R^2$ ranges from 0 to 1; values closer to 1 indicate better fit.

**1.3.4 Trend Analysis** Using least squares linear regression, we analyzed long-term RENDVI trends at pixel scale in buffer zones. Based on slope $k$ and F-test $P$ values, trends were classified as: significant degradation ($k < -0.01$, $P < 0.01$), mild degradation ($-0.01 < k < -0.005$, $0.01 < P < 0.05$), basically unchanged ($-0.005 < k < 0.005$, $P > 0.05$), mild improvement ($0.005 < k < 0.01$, $0.01 < P < 0.05$), and significant improvement ($k > 0.01$, $P < 0.01$).

**1.3.5 Correlation Analysis** We analyzed correlations between RENDVI and annual precipitation/temperature to assess climate factor impacts. The correlation coefficient $r$ ranges from -1 to 1; absolute values closer to 1 indicate stronger correlation:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where $x_i$ and $y_i$ are annual values of precipitation/temperature and RENDVI, $\bar{x}$ and $\bar{y}$ are means, and $n$ is sample size.

**1.3.6 Significance Testing** We performed significance tests on trend changes and correlations using F-tests. When $P < 0.05$, variables are considered significantly correlated.

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## 2. Results

### 2.1 Regional Climate Change

The study area experienced arid to semi-arid climate from 2018-2021. Annual precipitation showed a unimodal curve, peaking in July-August, while annual temperature peaked in June-July. Precipitation decreased ($k = -2.026$) from 432.1 mm, with fluctuations in 2019-2020. Temperature increased ($k = 0.0642$) from 8.4°C, with a 0.3°C decrease in 2019. July-August precipitation accounted for 65.7% of annual total, increasing 105.9 mm in 2021. The precipitation-temperature correlation was significantly negative ($r = -0.9327$, $P < 0.01$), indicating that increased precipitation corresponds to decreased temperature.

### 2.2 Temporal Dynamics of Vegetation Cover

Taking 2018 and 2021 as examples, we analyzed spatial vegetation cover changes. Based on RENDVI values, we classified cover as: bare land (<0.2), low (0.2-0.4), medium (0.4-0.6), high (0.6-0.8), and very high (>0.8). Spatial distribution showed that waste dump vegetation cover increased with mining activity, following a "mining while reclaiming" pattern. Except for Hongshengyuan, all mines had well-growing reclaimed vegetation on waste dumps in 2018. However, reduced precipitation and increased temperature in 2021 caused high-cover vegetation in waste dumps and comparison areas to evolve into low-cover vegetation, with noticeably poorer growth.

Analysis of vegetation cover area proportions (Figure 4) revealed that Wulanhada and Wujiata mines showed almost no change in bare land area despite ongoing mining, as mining pits moved while early pits were being reclaimed. Jingwei and Hongshengyuan mines increased bare land area (mainly mining pits) by 18.1% and 27.7% due to expanded mining intensity. Langwoqu mine reduced bare land area by 10.0% as all mining pits converted to waste dumps. In 2021, all mines showed sharp decreases in high-cover vegetation (24.4-29.5%) and increases in low-cover vegetation (20.3-29.4%). In contrast, comparison areas showed more stable vegetation growth unaffected by mining, though climate change caused high-cover vegetation degradation in 2021.

## 2.3 Vegetation Index Changes in Mining Areas and Waste Dumps

Vegetation index changes in mining areas and comparison zones (Figure 5) showed that all six indices in mining areas exhibited fluctuating "decrease-increase-decrease" patterns (except TCARI), with overall downward trends. NDVI had the largest fitting slope ($k = -0.0682$). In waste dumps and comparison zones (Figure 6), all indices decreased, with waste dump indices lower than comparison zones. Within the same mining area, the six indices showed similar patterns; using Hongshengyuan as an example, RENDVI and MSR_{RE} values were significantly higher, while TCARI was lower, but all showed downward trends. RENDVI showed the most consistent change pattern.

Normalized analysis revealed that red-edge vegetation indices (RENDVI, MSR_{RE}, TCARI) had smaller standard deviations and coefficients of variation than non-red-edge indices, indicating stronger resistance to external interference and more stable index fluctuations. This confirms that red-edge band indices offer higher reliability and sensitivity for monitoring subtle vegetation changes in mining areas.

Average slopes of the six vegetation indices for mining pits were all negative, with Hongshengyuan showing the most severe damage ($k = -0.2996$). Langwoqu' s mining pit evolved into a waste dump, yielding a positive average slope. Waste dump restoration effects varied: Hongshengyuan showed the best restoration with positive average slopes, while other mines showed negative slopes due to reduced vegetation coverage in 2021.

## 2.4 Vegetation Damage Changes in Buffer Zones

Open-pit mining disturbance extends 2-7 km with significant directional heterogeneity. We established 5 km buffer zones around mine edges to analyze surrounding vegetation changes. Pixel-by-pixel linear regression of RENDVI revealed that "significant degradation" areas in mine buffers ranged from 2.1-7.9%, while comparison zones had less than 0.5%. "Mild degradation" exceeded 50% in both buffers (55.4-75.0%) and comparison zones (up to 80.7%), indicating climate-driven degradation rather than mining impact. "Mild improvement" areas in buffers (13.9-23.9%) exceeded comparison zones, primarily in reclaimed waste dumps with dense artificial vegetation.

Spatially, "significant degradation" concentrated in mining pits where vegetation stripping caused severe damage. "Mild degradation" occurred mainly in unmined areas outside mines, affected by both mining and climate. "Mild improvement" areas corresponded to waste dumps where ecological restoration created high-density artificial vegetation.

### 2.5 Correlation Between Climate Factors and Vegetation Indices

Climate factors are key drivers of vegetation change. We analyzed correlations between NDVI and precipitation/temperature. Correlation coefficients ($r$) and F-test $P$ values were classified as: extremely significant positive ($r > 0$, $P < 0.01$), significant positive ($r > 0$, $P < 0.05$), non-significant positive ($r > 0$, $P > 0.05$), non-significant negative ($r < 0$, $P > 0.05$), significant negative ($r < 0$, $P < 0.05$), and extremely significant negative ($r < 0$, $P < 0.01$).

Spatial distribution of correlations (Figure 9) showed that significantly correlated areas were mainly outside mined zones. Within mining areas, regions significantly positively correlated with precipitation and negatively correlated with temperature were primarily newly reclaimed waste dumps. Statistics revealed that buffer and comparison zone NDVI was positively correlated with precipitation and negatively correlated with temperature, but the proportion of significant positive correlations with precipitation was smaller than significant negative correlations with temperature. This indicates that in desertified grasslands, vegetation NDVI responds more to temperature than precipitation.

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## 3. Discussion

### 3.1 Impacts of Mining Activities on Regional Vegetation

Open-pit coal mining should follow green development principles prioritizing ecological protection, making waste dump restoration critical. Using multiple red-edge indices from three perspectives (mining pits, waste dumps, buffer zones), we found that vegetation indices decreased due to coal mining across all mines, with mining pits showing the most severe damage (steepest slopes), consistent with Xing Longfei et al.' s findings. Buffer zone vegetation showed mild degradation from indirect mining impacts. Waste dumps were least affected due to active restoration under regulations like the "Land Reclamation Regulations," with some areas transitioning from bare land to low vegetation cover, showing improvement trends higher than non-mining areas (e.g., Hongshengyuan), aligning with Wu Qinyu et al.' s research in Ordos coal mining areas.

### 3.2 Impacts of Climate Change on Regional Vegetation

Analysis of 2018-2021 precipitation and temperature data revealed that July-August 2021 precipitation was exceptionally high (106.7% increase), while annual precipitation reached a low point; temperature rose about 0.5°C, with 2021 showing a high value. Vegetation index changes and spatial distribution showed that 2021 high-cover vegetation area decreased significantly while low-cover area increased, with overall degradation trends. Therefore, 2021 vegetation degradation was primarily climate-driven rather than mining-induced. Within waste dumps, climate contributions to vegetation improvement varied due to differences in reclamation age, vegetation type, community configuration, plant size, and management intensity. Liu Ying et al. found that mining area ecological environment changes were more stable than outside areas, similar to our degradation trend results.

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*Note: Figure translations are in progress. See original paper for figures.*