Postprint: Assessment of Vegetation Reconstruction Effects in Mining Areas Based on WorldView-2 Imagery

Authors: Zhang Zemin, Lü Changhe, Xie Miaomiao, Zhou Wei

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Abstract

Vegetation coverage reflects vegetation quality and is an important indicator for evaluating the effectiveness of vegetation reconstruction on reclaimed land in mining areas. This study selected the Antaibao mining area as the case study region, calculated vegetation coverage in the study area using a method that combines the mixed pixel model with field data validation based on new bands from high spatial resolution WorldView 2 (WV 2) imagery, and evaluated the vegetation reconstruction effectiveness. The main conclusions are as follows: (1) Based on the near-infrared 2 band and red band of WV 2 imagery, the vegetation coverage inversion value Fc2 obtained using the mixed pixel method was closest to the measured values, showing the strongest correlation (R2=0.934) and the smallest root mean square error (RMSE=0.048); (2) The overall vegetation reconstruction effect in the study area was relatively good, with areas of medium, relatively high, and high vegetation coverage accounting for over 60% of the study area, while low vegetation coverage only accounted for 22.09%. Influenced by the duration of vegetation reconstruction and management measures, there were differences in vegetation reconstruction status among different reclamation areas. The inner dump, west dump, and south dump showed better vegetation reconstruction effects, while the west dump expansion area had relatively poorer vegetation conditions, with the proportions of medium and above vegetation coverage being 75.24%, 68.35%, 68.20%, and 22.29%, respectively. (3) Regarding vegetation combination patterns, the tree-shrub-grass pattern showed the best reconstruction effect (based on canopy coverage), followed by the tree-grass pattern, with other patterns such as shrub-grass, grassland, and natural recovery areas decreasing sequentially. Soil surface moisture content increased with increasing vegetation coverage on reclaimed land, indicating that vegetation reconstruction status plays an important role in soil surface water retention.

Full Text

Preamble

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Evaluation of Vegetation Restoration Effects in Mining Areas Based on WorldView-2 Images

ZHANG Zemin[1],[2], LÜ Changhe[1],[2], XIE Miaomiao[3], ZHOU Wei[1]

[1]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]College of Land Science and Technology, China University of Geosciences; Key Laboratory of Land Consolidation and Rehabilitation, Ministry of Land and Resources, Beijing 100083, China

Abstract

Vegetation coverage fraction reflects vegetation quality and is an important indicator for evaluating vegetation restoration effects on reclaimed land in mining areas. This study selected the Antaibao mining area as a case study and used a combination of mixed pixel model and field data validation to calculate vegetation coverage based on high spatial resolution WorldView-2 (WV-2) imagery. The new spectral bands of WV-2 imagery were utilized to assess vegetation restoration effects. The main conclusions are as follows: (1) Using the near-infrared 2 band and red band of WV-2 imagery, vegetation coverage fraction retrieved by the mixed pixel method was closest to field-measured values, showing the strongest correlation ($R = 0.934$) and minimum root mean square error ($RMSE = 0.048$). (2) The study area showed good overall vegetation restoration, with moderate-to-high vegetation coverage accounting for 75.24%, 68.35%, and 68.20% in the Inner Dump, West Dump, and South Dump respectively, while the expanded West Dump area had only 22.29% moderate-to-high coverage. (3) Regarding vegetation combination patterns, the tree-shrub-grass configuration showed the best restoration effect, followed by the tree-grass pattern, while shrub-grass, grass-only, and natural restoration showed progressively poorer effects. Soil surface moisture content increased with vegetation coverage, indicating that vegetation restoration status plays an important role in soil surface water retention.

Keywords: WorldView-2; vegetation coverage fraction; Antaibao mine; mixed pixel model

Introduction

As an important energy source in China, large-scale coal mining and utilization meet the energy demands of socio-economic development while causing serious ecological and environmental problems [1-3]. Particularly in open-pit coal mines, the large mining area causes tremendous negative impacts on local ecological environments. Vegetation is the most sensitive environmental factor in mining area ecosystems, and its growth status directly or indirectly affects other environmental factors, making it key to comprehensive ecosystem recovery [4]. Effectively monitoring vegetation restoration effects on reclaimed land in mining areas is an important means for scientific assessment and revealing reclamation effectiveness.

Vegetation coverage fraction is a comprehensive reflection of vegetation growth and quality, and serves as an important indicator for evaluating vegetation restoration effects on reclaimed land in mining areas [5-8]. Traditional measurement methods include visual estimation and instrument-based field methods [9], which, while accurate, are costly and time-consuming. Since the 1970s, remote sensing-based vegetation coverage extraction methods have developed rapidly. Early approaches based on Landsat MSS and NOAA/AVHRR imagery used simple linear regression to estimate vegetation coverage [10]. Subsequently, various vegetation index methods using multi-band imagery from Landsat TM, MODIS, and other sensors were proposed, including Normalized Difference Vegetation Index (NDVI) [12-15], Perpendicular Vegetation Index (PVI), Soil Adjusted Vegetation Index (SAVI), and Modified Soil Adjusted Vegetation Index (MSAVI) [16-20]. Additionally, pixel decomposition model methods based on spectral mixture analysis were developed [21-22]. Some of these indices and methods have been applied in mining area reclamation effect assessment. For example, Liu et al. analyzed vegetation growth changes in the Pingshuo Antaibao coal mine reclamation area [23]; Zhao et al. used Landsat NDVI with a pixel dichotomy model to estimate vegetation coverage changes in the Yulin mining area [24]; Su et al. used vegetation coverage calculated by similar methods to explore multi-temporal vegetation growth status and spatiotemporal variation characteristics in the Haizhou open-pit coal mine dump of Fuxin City [26].

However, most of the above data and methods are based on relatively low spatial resolution imagery (e.g., TM, MODIS), suitable for vegetation coverage inversion in large regions but insufficient for high-precision assessment of vegetation restoration status in small-area mining sites. This study selected the Antaibao open-pit mine in the Pingshuo mining area, using high spatial resolution WorldView-2 (WV-2) imagery and field measurement data. Leveraging the advantages of WV-2' s new spectral bands, we employed the mixed pixel model method, compared the accuracy of different vegetation indices for coverage extraction, determined the optimal index method, and evaluated vegetation restoration effects in the case study area to provide references for reclamation vegetation restoration measures and post-mining land reclamation work.

1 Study Area Overview

The Antaibao open-pit coal mine is located in Pinglu District, Shuozhou City, Shanxi Province, within a loess hilly region. The area has a continental monsoon climate with large diurnal temperature variation and distinct winter-summer contrast. The multi-year average precipitation is 430 mm, with precipitation mainly concentrated in July, August, and September. The average annual evaporation is 3-4 times the precipitation amount, causing severe water erosion in summer. The main zonal soil is chestnut soil. The harsh vegetation growth environment, combined with mining activities since the 1980s, has caused severe damage to soil and vegetation [27].

Since the start of production, Antaibao mining area has dramatically altered original topography and strata through excavation and dumping. In the later mining period, an integrated mining-reclamation model was adopted: mining waste was stacked to form platforms 100-150 m high with 20-40 m height differences between benches, covered with topsoil, and then vegetation restoration was implemented on each platform and slope. The study area contains four dumps: South Dump, West Dump, Inner Dump, and West Dump expansion area, with different reclamation times, durations, and vegetation configuration types [29].

The South Dump began reclamation in 1987 and stopped in 1997, with main vegetation types including elm, sea buckthorn, alfalfa, and various grasses in a shrub-grass interplanting pattern. The West Dump started reclamation later, with vegetation including sea buckthorn, elm, and amorpha in tree-grass interplanting or intercropping patterns. The West Dump expansion area began reclamation most recently (starting in 2004), with vegetation types mainly pine, locust, and elm. The Inner Dump is the only internal dump in the study area, reclaimed starting in 1992. There is also a large area of natural restoration land. Protective forest belts around each dump mainly use locust interplanted with elm or Xinjiang poplar, with caragana or sea buckthorn intercropped in between [30].

[Figure 1: see original paper] Schematic geographical location of study area

2 Data Sources and Preprocessing

The remote sensing data used in this study is WorldView-2 imagery, which consists of a 0.5 m spatial resolution panchromatic band and eight multispectral bands [31-32]. WV-2 imagery has richer multispectral bands than traditional imagery, including four color bands (coastal, blue, green, yellow), one red edge band, and two near-infrared bands (NIR1, NIR2). These bands can directly or indirectly reflect vegetation growth status and are important for quantitative calculation and analysis of vegetation quality indicators, as well as for vegetation parameter inversion. The NIR2 band partially overlaps with NIR1, supports vegetation analysis and biomass research, enhances vegetation features, and is less affected by the atmosphere.

Spectrum range and spatial resolution of WV-2 image bands

Band	Spectral Range (m)	Spatial Resolution (m)
Coastal	0.40-0.45	2.0
Blue	0.45-0.51	2.0
Green	0.51-0.58	2.0
Yellow	0.59-0.63	2.0
Red	0.63-0.69	2.0
Red Edge	0.71-0.75	2.0
NIR1	0.77-0.89	2.0
NIR2	0.86-1.04	2.0
Panchromatic	0.45-0.80	0.5

The WV-2 imagery preprocessing included: (1) radiometric calibration to convert digital numbers to radiance, (2) atmospheric correction to convert radiance to surface reflectance and eliminate errors from atmospheric scattering and reflection, (3) geometric correction, and (4) image cropping to the study area boundary. The preprocessed imagery retained multispectral characteristics while spatial resolution was improved to 0.5 m. MODIS data from the same month in 2012 were used to calculate the Temperature Vegetation Drought Index (TVDI) for the study area, with elevation data and field soil moisture measurements used for correction [33-34]. A vegetation type distribution map was created using supervised classification of the WV-2 imagery.

[Figure 2: see original paper] True color image of Antaibao dumps, TVDI distribution, and vegetation types

3 Canopy Coverage Inversion

The mixed pixel model assumes that the land surface consists of two components: pure vegetation cover and non-vegetation cover surface. The proportion of vegetation-covered area in a pixel represents the pixel’ s vegetation coverage. This model combines vegetation indices with pixel dichotomy to calculate vegetation coverage [36]. Traditional mixed pixel models for vegetation coverage calculation are mainly based on NDVI derived from near-infrared (NIR) and red (R) bands of conventional imagery. Confidence intervals are determined using field-measured bare ground and full vegetation cover sample areas and their corresponding remote sensing values, with NDVI values for bare ground (NDVI_s) and full vegetation cover (NDVI_v) used to calculate vegetation coverage for the entire study area.

This study utilized WV-2’ s unique red edge band (RE) and combined it with traditional bands (R) to calculate different NDVI forms. Confidence intervals were determined based on field-measured bare ground and full vegetation cover sample areas and their corresponding values from different calculation methods. Vegetation coverage based on different band combinations was then calculated.

Four NDVI combinations were used: - NDVI = (NIR - R) / (NIR + R) - NDVI = (NIR - R) / (NIR + R) - NDVI = (NIR - RE) / (NIR + RE) - NDVI = (NIR - RE) / (NIR + RE)

The vegetation coverage fraction (F_c) for each band combination was calculated as: F_c = (NDVI - NDVI_s) / (NDVI_v - NDVI_s)

where F_c , NDVI_s , and NDVI_v are the vegetation coverage fraction, bare ground NDVI, and full vegetation cover NDVI for the nth band combination (n = 1, 2, 3, 4), respectively.

4 Accuracy Verification

To quantitatively evaluate the inversion accuracy of canopy coverage derived from different band combinations, 40 permanent sample plots were established in the study area, distributed across the South Dump, West Dump, Inner Dump, and West Dump expansion area. Considering vegetation distribution, 40 sample points were laid out on platforms of different heights. Field data collection was conducted using a handheld GPS to record locations and a digital camera to photograph each sample point. Photographs were taken with the camera as vertical as possible to correctly reflect the proportion of vegetation vertical projection area covering the ground [37]. Each sample point' s surrounding environment was recorded as a reference factor for data screening.

Adobe Photoshop CS5 was used to analyze the proportion of vegetation in each valid sample point photo, with the result representing the field-measured vegetation coverage. To compare the accuracy of vegetation coverage calculated from different bands, field data were overlaid with four groups of inversion results. SPSS Statistics 20 software was used to conduct correlation analysis between field vegetation coverage and the four inversion results, obtaining correlation coefficients and root mean square error (RMSE) [38-39].

The correlation coefficient (R) and RMSE were calculated as: $R = \Sigma(X - \bar{X})(Y - \bar{Y}) / \sqrt{[\Sigma(X - \bar{X})^2 \Sigma(Y - \bar{Y})^2]}$ $RMSE = \sqrt{[\Sigma(Y - X)^2 / K]}$

where K is the number of sample points, i is the sample point number, X is image-derived vegetation coverage, and Y is field-measured vegetation coverage.

5 Results Analysis

5.1 Results and Accuracy Verification

Based on the mixed pixel model described above, vegetation coverage maps of the study area were obtained from different band combinations. While the spatial distributions showed some similarity, clear differences existed among them. The accuracy assessment of the four canopy coverage inversion results is shown in Table 2.

Correlation coefficients between observed and estimated coverage

Estimated Coverage	Pearson Coefficient	Significance	RMSE
F_c (NIR +R)	0.928	<0.001	0.458
F_c (NIR +R)	0.958	<0.001	0.048
F_c (NIR +RE)	0.913	<0.001	0.500
F_c (NIR +RE)	0.934	<0.001	0.355

The results show that vegetation coverage inversion using WV-2' s near-infrared 2 band and red band (F_c) had the strongest correlation with field measurements (R = 0.958) and the smallest RMSE (0.048). This was followed by the near-infrared 1 band and red edge band combination (F_c , R = 0.934, RMSE = 0.355). The lower accuracy of the red edge band combinations may be because the study period was at the end of the vegetation growing season, when vegetation leaves begin to wither, chlorophyll is replaced by xanthophyll, causing red edge band redshift and complex adjustments in vegetation reflectance [40-41].

[Figure 3: see original paper] Distribution map of vegetation coverage in the study area based on different WV-2 band combinations

[Figure 4: see original paper] Scatter plot of vegetation coverage fraction obtained by WV-2 imagery and field measurements

5.2 Vegetation Restoration Effect Assessment

Based on the validation results, the study area vegetation coverage was calculated using the optimal near-infrared 2 band and red band combination. In the resulting map, most of the South Dump and central West Dump appear dark-colored, indicating high vegetation coverage and good restoration status. The southern Inner Dump and most of the West Dump expansion area appear light-colored, indicating poor vegetation growth or near-bare conditions. In the West Dump expansion area and northwestern South Dump, light-colored or even bright white areas appear, representing very poor vegetation growth or bare ground.

The average vegetation coverage for each dump was calculated, and the entire study area' s vegetation coverage was classified into five levels: low (0-0.2), lower (0.2-0.4), moderate (0.4-0.6), higher (0.6-0.8), and high (0.8-1.0). The distribution map of vegetation coverage grades for the entire study area and each dump was generated using ArcMap.

Overall, the study area' s average vegetation coverage was 0.501. Moderate and above vegetation coverage accounted for 53.70% of the study area, while low vegetation coverage accounted for only 22.09%. Lower and moderate coverage accounted for 24.22% and 32.47% respectively. Higher and high coverage areas together comprised 21.22% of the study area. The average vegetation coverage values for Inner Dump, West Dump, South Dump, and West Dump expansion area were 0.473, 0.488, 0.501, and 0.260 respectively. The proportion of moderate and above vegetation coverage in each dump was 68.20%, 68.35%, 75.24%, and 22.29% respectively. Notably, the West Dump expansion area had a high proportion (47.11%) of low vegetation coverage (0-0.2), and its combined lower and low coverage proportion reached 68.09%. In contrast, the higher and high coverage proportion in the West Dump expansion area was much smaller than in the other three dumps. These data demonstrate significant differences in vegetation restoration status among different dump reclamation areas, with the West Dump expansion area showing relatively poor restoration effects while the South Dump shows better restoration status.

[Figure 5: see original paper] Distribution of vegetation coverage fraction in the study area and composition of different coverage grades of each dump

5.3 Effect Analysis

Vegetation restoration effects in mining reclamation areas are mainly influenced by site conditions such as vegetation configuration types, reclamation measures, and reclamation duration. Supervised classification of remote sensing imagery identified five vegetation reclamation patterns in the Antaibao mining area: tree-shrub-grass combination, tree-grass interplanting, shrub-grass combination, grass-only vegetation, and natural restoration [43]. Over time and through alternating influences between vegetation and environmental factors, areas with composite vegetation configuration patterns become more diverse and structurally complex, while areas with single reclamation patterns have relatively simple vegetation types and structure.

In terms of reclamation duration and vegetation configuration patterns, the South Dump was reclaimed earliest (starting 1987) and has formed a relatively complete and stable ecosystem, resulting in the highest average vegetation coverage and largest proportion of high coverage pixels. The West Dump and Inner Dump followed later. The West Dump expansion area was reclaimed most recently (starting 2004), mainly using tree-grass and grass-only patterns with more natural restoration land, resulting in the lowest average vegetation coverage and largest proportion of lower and low coverage areas. Another factor is coal gangue spontaneous combustion, which occurred more frequently in the West Dump and South Dump, causing irreversible damage to vegetation in reclamation areas and leading to uneven vegetation status.

Regarding the influence of vegetation configuration on restoration effects, analysis using ArcMap software showed that vegetation coverage and restoration effects are significantly affected by vegetation type configuration during reclamation. Vegetation coverage values from highest to lowest for different combination types were: tree-shrub-grass > tree-grass > shrub-grass > grass-only > natural restoration. Additionally, as vegetation coverage increased, TVDI values showed a decreasing trend, indicating that soil surface moisture content increases with vegetation coverage in reclaimed land. This demonstrates that vegetation restoration plays an important role in soil surface water retention [45].

Changes in vegetation coverage fraction with different vegetation restoration types and TVDI

Vegetation Types Allocation	Average Vegetation Coverage	Temperature Vegetation Drought Index (TVDI)
Combination of grass, shrub and trees	0.780	0.359
Inter-planting of grass and trees	0.666	0.398
Combination of shrub grass	0.413	0.455
Grass vegetation	0.358	0.460
Natural restoration vegetation	0.290	0.469

6 Discussion

The study demonstrates that high spatial resolution and multispectral WV-2 imagery has clear feasibility for vegetation coverage inversion. The overall vegetation restoration effect in the study area is good, with reclaimed areas showing much better vegetation status than naturally restored areas. However, it should be noted that due to spontaneous combustion or other stress factors, longer reclamation time does not necessarily guarantee higher vegetation coverage. The vegetation growth status in some individual areas within reclamation zones remains concerning and requires continued artificial maintenance measures.

The relatively poor local restoration effects may be attributed to the harsh local climate conditions, with annual precipitation around 400 mm that cannot meet reclamation vegetation water requirements. Therefore, during vegetation restoration in reclamation areas, it is advisable to select local shrubs, trees, and grasses with mixed configurations that help maintain soil water and fertility, rather than using exotic species or single vegetation types. Additionally, reclaimed land consists mostly of coal gangue hills, and internal complex physical and chemical changes, heating, or spontaneous combustion can cause irreversible damage to vegetation, affecting restoration outcomes. Vegetation restoration in reclamation areas is a long-term process affected by complex factors, urgently requiring a multi-indicator, multi-temporal monitoring system to provide feasible recommendations for reclamation vegetation restoration measures and post-mining land reclamation work.

7 Conclusion

Using a combination of mixed pixel model and field data validation, this study compared the accuracy of different band combinations for vegetation coverage inversion and conducted statistical analysis of the results. The main conclusions are:

1. Vegetation coverage inversion values calculated using WV-2's near-infrared 2 band and red band (F_c) were closest to field measurements, with the strongest correlation ($R = 0.958$) and smallest RMSE (0.048). The near-infrared 1 band and red edge band combination (F_c) ranked second ($R = 0.934$, $RMSE = 0.355$).
2. The overall vegetation restoration status in the study area was good, with moderate and above vegetation coverage accounting for 53.70% of the area. Affected by reclamation duration, vegetation configuration types, and gangue spontaneous combustion, significant differences existed in vegetation coverage among different areas. The average vegetation coverage values for Inner Dump, West Dump, South Dump, and West Dump expansion area were 0.473, 0.488, 0.501, and 0.260 respectively, with moderate and above coverage proportions of 68.20%, 68.35%, 75.24%, and 22.29%. The South Dump and West Dump showed good restoration effects, while the West Dump expansion area showed poor restoration.
3. Vegetation coverage is significantly affected by vegetation type configuration during reclamation. Coverage values from highest to lowest were: tree-shrub-grass > tree-grass > shrub-grass > grass-only > natural restoration. As vegetation coverage increased, soil surface moisture content correspondingly increased, indicating that vegetation restoration contributes to soil surface water retention.

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