IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 16, 2021, accepted December 1, 2021, date of publication December 6, 2021, date of current version December 17, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3133478

Assessment of the Ecological Impacts of Coal Mining and Restoration in Alpine Areas: A Case Study of the Muli Coalfield on the Qinghai-Tibet Plateau

DONGZHU YUAN[1], ZHENQI HU[1,2], KUN YANG[1], JIAXIN GUO[1], PENGYU LI[1], GENSHENG LI[2], AND YAOKUN FU[1]

[1]School of Geoscience and Surveying Engineering, China University of Mining and Technology-Beijing, Beijing 100083, China
[2]School of Environment and Spatial Informatics, China University of Mining and Technology, Xuzhou 221116, China

Corresponding author: Zhenqi Hu (huzq1963@163.com)

This work was supported in part by the Jiangsu Province University Innovation Team Project, and in part by the Jiangsu Province University Innovation Talent Project.

ABSTRACT Surface mining inevitably impacts the ecological environment, especially in alpine and fragile mining areas. Thus, it is worth discussing the dynamic impact process of mining on regional land use and landscapes. In this study, we took the Muli coalfield, a typical alpine mining area on the Qinghai-Tibet Plateau (QTP), as an example and analyzed the changing characteristics of the eco-environment in 2003-2010 (low-intensity mining), 2010-2014 (large-scale mining), and 2014-2020 (restoration) through a land use transfer matrix, landscape fragmentation index and vegetation cover based on remote sensing data, and discussed the problems and lessons learned. The results show that: (1) the land use transfer process changed from active to basically stable. During the mining phase, the land use transfers were complex and mainly consisted of the transfers of grassland to production land. The land use transfers during the restoration phase were not obvious. (2) Natural landscape types (e.g., river and grassland) were separated by surface mining. In terms of landscape fragmentation, the patch densities showed an increasing trend, while the patch shape fragmentation index showed first decreased and then increased. Additionally, the level of landscape fragmentation during the restoration phase did not change significantly. (3) The changes in average vegetation cover in the gangue fields occurred in four stages: i) gradually decreases from 2003 to 2010, ii) rapid decreases from 2010 to 2014, iii) increases from 2014 to 2017, and iv) further decreases again after 2017. (4) We summarized the lessons learned from the mining and restoration processes and provided a reference for addressing the conflict between mineral exploitation and environmental protection in ecologically fragile alpine mining areas.

INDEX TERMS Alpine grassland, eco-environment, restoration, FVC, muli coalfield, Qinghai-Tibet Plateau.

I. INTRODUCTION

Mineral resources exploitation, especially surface mining, causes serious damage to the land [1] and poses a series of ecological challenges, such as air pollution [2], vegetation degradation [3], soil erosion [4], and loss of biodiversity [5], [6]. In particular, a high-altitude ecosystem region, the Qinghai-Tibet Plateau (QTP), where alpine grassland is widely distributed [7], plays a crucial role in regulating regional ecological functions, water cycles, and carbon cycles [8]–[10], but is also an ecologically fragile area with the most serious grassland degradation [11]. The ecosystems on the QTP respond strongly to the effects of climate change and anthropogenic activities [12], [13]. Zhang *et al.* [14] used remote sensing and climate data to analyze the spatial patterns of the Vegetation Peak-Normalized Difference Vegetation Index (VP-NDVI) of grasslands on the Tibetan Plateau from 1981-2001, and the driving forces of climate and

The associate editor coordinating the review of this manuscript and approving it for publication was John Xun Yang.

anthropogenic. Wang *et al.* [15] extracted the phenological metrics of the alpine meadows for ten years and found that precipitation was the main influencing factor for grassland vegetation changes. Wang *et al.* [16] analyzed the land change trends on the QTP from 2001-2015, which revealed the high sensitivity of the QTP to climate change and human activities. Ran *et al.* [17] discussed the vegetation changes and driving factors of the alpine grassland ecosystem and concluded that alpine grasslands have the lowest vegetation stability. The above studies examined the ecological environmental changes in the QTP by analyzing the growth of vegetation (mainly the alpine meadows), which proves the fragility of alpine meadows on the QTP. However, most of these studies have emphasized the ecosystem changes in the QTP at large scales, and the main drivers are climate-related, which do not accurately reflect the ecosystem characteristics of mining areas.

The Muli coalfield is located at the southern foot of the Qilian Mountains in the northern part of the QTP and is the largest surface coal mine in Qinghai Province. The mining activities on the QTP can cause severe damage to alpine grasslands, so it is imperative to analyze the temporal and spatial patterns of the impact of long-term open-pit mining on the ecological environment in alpine regions. Land use changes and landscape pattern changes are the most intuitive manifestations of large-scale ecological changes. Qian *et al.* [18] analyzed the land use changes and landscape pattern responses in and around mine areas based on remote sensing images obtained from 1976 to 2016. The results showed that landscape pattern responses mainly occurred within 6 km of the mine area. By calculating the ecosystem service values (ESVs) in and around the mine areas from 1975 to 2016 and by comparing these with the mining benefits, Qian *et al.* [19] concluded that scattered and uncontrolled mining accelerates the loss of ESVs and that regions with lower ESVs are more favorable for mining. Wu *et al.* [20] detected abrupt changes in vegetation cover from multitemporal images to determine the timing and scale of mining activities. The results showed that mining activity in the Muli coalfield began in 2003. However, these studies mainly focused on the ecological impact of surface mining in the Muli coalfield, and there has been little discussion on the environmental changes after ecological restoration in recent years.

In 2014, Greenpeace [21] exposed illegal mining in the Muli coalfield due to its severe damage to the alpine meadow ecosystem and ecological damage to China's national nature reserves and the source of the Yellow River which drew widespread global attention. The relevant departments of the Chinese government attached great importance to this matter and ordered all illegal mining activities in the area to stop and made every effort to promote the eco-environmental management of alpine and high-altitude mining areas. It has been six years since the ecological restoration began, so it is necessary to examine the restoration effect of the mining areas. Remote sensing technology offers a viable solution for this purpose. Yang *et al.* [22] obtained continuous detections of the vegetation dynamics in open-pit mining areas to analyze the effects of reclamation. Zhang *et al.* [3] calculated the fractional vegetation cover (FVC) and vegetation index of reclaimed dumps and explored the spatial distributions of vegetation cover using the Moran index. Xiao *et al.* [23] combined the Google Earth Engine (GEE) platform with time-series Landsat images and the LandTrendr algorithm to determine the year that recovery occurred with a 78.57% accuracy. Ren *et al.* [24] obtained NDVI datasets to analyze the effects of the post-reclamation management of coal waste dumps on vegetation recovery.

The remote location, poor climatic conditions, and inconvenient transportation of the Muli coalfield cause the local economy to be backward. Mineral extraction plays a crucial role in the economic development. However, while providing an important contribution to the economy, mineral extraction inevitably causes damage to the regional eco-environment that cannot be ignored. Therefore, discussing the relationship between economic development and environmental protection in ecologically fragile areas has become a hot topic after the exposure of Muli's illegal mining incidents.

This paper aims to identify the path for the coordinated development of the environment and resources in ecologically fragile areas by quantitatively assessing the impact of mining and restoration on the ecological environment in the Muli coalfield and analyzing the characteristics and patterns of the impact. Therefore, the highlights of this study are: (1) to obtain the spatial and temporal land use distribution and evaluate the land use transfers in the mining areas, (2) to analyze the changes in landscape patterns in the mining areas, (3) to explore in detail the impacts on vegetation under the effects of coal mining and restoration, and (4) to summarize the dilemmas of the Muli coalfield and propose mitigation measures.

II. MATERIALS AND METHODS

A. STUDY AREA

The Muli coalfield (longitude: 98°50′E∼100°50′E, latitude: 37°30′N∼38°15′N) is located in the Qinghai Province at an average elevation of 4,100 m (Fig. 1). It is the largest coal mining area in Qinghai and is an important coking coal producer in northwest China. The Muli coalfield consists of four mining districts, Juhugeng, Jiangcang, Duosuogongma, and Hushan, which are distributed in a northwest-oriented strip. The coalfield is 50 km long from east to the west and 8 km wide from north to south, with a total area of approximately 400 km^2. The average annual temperature here is – 5.1°C [25], and the annual precipitation and evaporation are 477.1 mm and 1,049.9 mm, respectively [26].

The ecological status of the region is extremely important as it lies at the origin of the Datong River, which is a major tributary of the Yellow River and is an important part of the Qilian Mountains region's water conservation areas and ecological safety shelter [27]. In addition, the mining area is

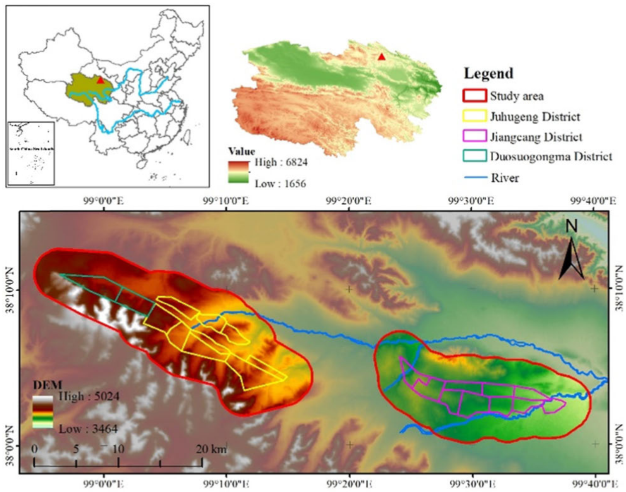

FIGURE 1. Location of the study area.

situated in the plateau alpine region, which is a typical ecologically fragile area on the QTP, with large areas of permafrost and alpine meadows. The regional ecology is unstable and fragile, therefore, it is highly sensitive to the disturbances from artificial activities. Once it is destroyed, it will take a long period of succession to gradually transition to normal conditions.

Twenty-one coal mines are planned in the Muli coalfield, of which 12 have been surface mined (four in the Jiangcang District, six in the Juhugeng District, and two in the Duosuogongma District). In 2003, low-intensity mining began at a few scattered sites, with large-scale production starting after 2010. According to the mine design, except for the Juhugeng No. 3 mine, which involves surface mining, all other mines were to be operated by using underground mining. Owing to the convenience and low costs, all of the mines were mined in an open-pit, which contradicted the originally approved mining method. Greenpeace announced the ecological damage caused by crude and extensive coal mining in fragile alpine areas in 2014. Then, all mining activities in the area ceased. Based on the development history of the Muli coalfield, we discussed the ecological impacts of surface mining for three phases: the first mining phase (2003-2010), the second mining phase (2010-2014), and the restoration phase (2014-2020).

The mining activities in Muli are mainly concentrated in Juhugeng (JHG) and Jiangcang (JC). There are only small-scale mining traces in Duosuogongma, so this district was merged into Juhugeng for discussion. Therefore, this study focused on the mines in JHG and JC (Fig. 1). Considering the large impact of coal mining on the surrounding environment, the area of this study was defined to be within the mine boundary and its 3km buffer zone based on site investigation.

B. DATA SOURCES AND PROCESSING

In this study, two data sources were used to obtain land cover and FVC data in the study area: Landsat TM/OLI images from July and August 2003-2020 (https://earthexplorer.usgs.gov/) and Gaofen-1 PMS images for 2014 and 2020 (https://www.sasclouds.com/). The Gaofen-1 satellite began providing data services in 2013 and acquires images in four multispectral bands (with a resolution of 8 meters) and one panchromatic band (with a resolution of 2 meters).

Preprocessing operations were applied to all images by using ENVI 5.3 and ArcGIS 10.5, which included radiometric correction, geometric correction, and image stitching. The preprocessed images from Landsat in 2003 and 2010 and from Gaofen-1 in 2014 and 2020 were used to map the land cover of the study area. By referencing the classification system of the Chinese Academy of Sciences for land-use monitoring by using remote sensing and considering the needs of the study, we classified the land uses in the Muli coalfield into grassland, water and wetland, productive and living land and unutilized land. First, a supervised classification method (maximum-likelihood classification) was applied to categorize the different land cover types in the preprocessed images. Manual visual interpretations were then used to further improve the classification accuracies in conjunction with the field survey maps that were collected from the local government. Finally, 30-50 sample validation areas were selected for each cover type from Google Earth software and field survey maps to evaluate the accuracy of the land cover classification in this study by calculating the Kappa coefficients of the classification results through a confusion matrix in each period. The workflow for the land cover classification in our research is shown in Fig. 2. The Kappa coefficients for the four periods of land cover classifications were 88.82%, 87.17%, 90.74% and 89.00%, respectively. The increase in image resolution led to an increase in the number of mixed pixels [28], which affected the classification accuracy. Nevertheless, our research used manual visual interpretations to improve the accuracy as much as possible, which resulted in no major differences in the land cover classification results among the four periods.

On this basis, the main land-use elements were finely classified to form a secondary land-use classification (Tab. 1). The multiyear NDVIs in the Muli coalfield were calculated using the preprocessed Landsat TM images from 2003 to 2020.

C. RESEARCH METHODS

1) LAND USE TRANSFER MATRIX

The land use transfer matrix is derived from the quantitative description of system states and state transfers used in system analysis [29], [30]. It reflects the information on the dynamics of the transformations between the areas of each category at the beginning and end of a period of time in a certain region; its general form is:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix} \tag{1}$$

TABLE 1. Land use classification system for the Muli coalfield.

Land use type	Secondary classification	Description
Grassland	High coverage grassland	Grassland with a vegetation coverage greater than 50%
	Medium coverage grassland	Grassland with 20-50% vegetation coverage
	Low coverage grassland	Grassland with 5-20% vegetation coverage
Water and wetland	River	Land formed by rivers, artificial canals, snowmelt runoff, etc.
	Lake/pond	Land below the perennial water level in natural or artificial water storage areas
	Marsh	Land with flat and low-lying terrain, poor drainage, long-term humidity, seasonal ponding or frequent ponding, and wetland plants on the surface
Productive and living land	Mining pit	Land formed into pits by surface mining
	Gangue filed	Land occupied for slag stockpiling
	Material pile	Land occupied for of mineral products accumulation
	Production construction site	Land occupied by buildings such as office premises and plants for production activities
	Living construction site	Land occupied by domestic buildings
	Traffic facility	Land used for the construction of transport facilities
	Other land	Land for other human activities
Unutilized land	Bare rock gravel land	Land with a rock or gravel surface and vegetation coverage of less than 5 %

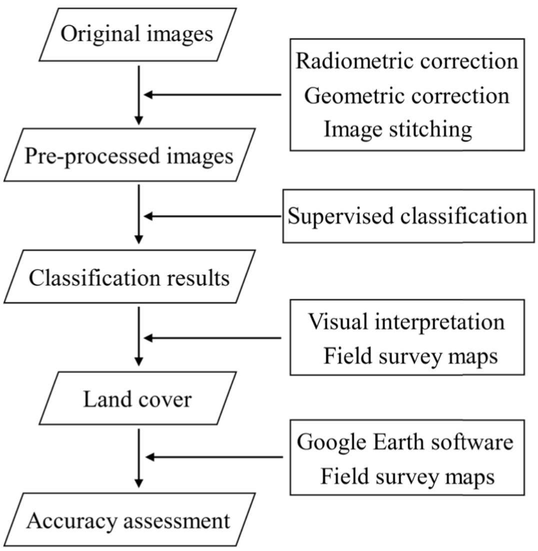

FIGURE 2. Workflow for land cover classification.

where n stands for the number of land use types before and after a transfer; i, j $(i, j = 1, 2 \ldots, n)$ are the land use types before and after a transfer, respectively; and S_{ij} is the area converted from the pre-transfer land use type i to the post-transfer land use type j after a transfer. Each element in a matrix row represents the flow information from the pre-transfer land use type i to the post-transfer land use types. Each element in a matrix column represents the source information for the post-transfer land use type j from the pre-transfer land use types.

The single land use dynamic degree (LUDD) is the ratio of the total change of one land use type to the sum of the total changed and the unchanged land use types [31]. It is calculated as follows:

$$LUDD_i = \frac{TC_i}{TC_i + S_{ii}} \times 100\% \tag{2}$$

where TC_i stands for the total change in the area of land use type i, which is the sum of the newly increased area and the decreased area. S_{ii} stands for the area of pre-transfer land use i that was not transformed during the study period.

The total land use dynamic degree (TLUDD) is the ratio of the total decrease (or total increase) of various land use types in the region to the entire area of the region and is used to measure the comprehensive activity level of regional land use changes [31]. The corresponding equation is:

$$TLUDD = \frac{D_T(I_T)}{\sum_{i=1}^{n} \sum_{j=1}^{n} S_{ij}} \times 100\% \tag{3}$$

where D_T (I_T) represents the area decrease (or increase) of all land use types during the study period.

2) LANDSCAPE INDEX

The patch density (PD) and shape fragmentation index (FS) were selected to quantitatively analyze landscape pattern changes, mainly landscape fragmentation.

The PD is the total number of patches per 100 hectares in the landscape [32]. The PD can indicate the extent to which the landscape matrix is segmented by patches of that type [33]. The larger its value, the greater the spatial heterogeneity, i.e., the higher the fragmentation of a landscape element type or the landscape; conversely, the landscape type is well preserved, and the connectivity is high. However, the PDs can only be used for cross-sectional comparisons, so other indicators are needed to describe the landscape fragmentation. In this study, the PDs were calculated using ArcGIS 10.5.

The shape fragmentation index contains the mean patch shape fragmentation index (FS_1) and area-weighted mean shape fragmentation index (FS_2) [34]–[36]. When the values of both indices are high, the fragmentation of the landscape shapes is more serious. The relevant formulas are as follows:

$$FS_1 = 1 - \frac{1}{MSI} \tag{4}$$

$$FS_2 = 1 - \frac{1}{ASI} \tag{5}$$

$$MSI = \frac{\sum_{i=1}^{N} SI_i}{N} \tag{6}$$

TABLE 2. The areas of the land use types of Juhugeng and Jiangcang in 2003/2010/2014/2020 (hm^2).

Land Use	Juhugeng				Jiangcang			
	2003	2010	2014	2020	2003	2010	2014	2020
High coverage grassland	763.88	763.88	714.49	714.49	12549.62	11849.28	11521.86	11524.82
Medium coverage grassland	14575.66	12332.25	10439.23	10351.09	3891.89	3606.22	3582.73	3608.04
Low coverage grassland	8081.20	7704.78	7363.71	7294.68	4741.01	4701.66	4755.68	4751.73
River	626.16	669.15	573.05	586.77	1061.52	1060.18	996.42	971.10
Lake/pond	432.76	292.11	331.04	318.44	55.57	52.46	53.98	55.33
Marsh	143.18	142.07	142.04	142.04	-	-	-	-
Mining pit	1.38	534.59	1430.52	1466.47	0.47	226.48	350.44	347.22
Gangue field	0.56	437.77	1556.91	1664.31	0.25	429.81	585.14	582.27
Material pile	-	20.79	95.02	71.72	-	17.73	39.88	12.96
Production construction site	-	95.59	376.67	281.35	-	75.50	111.38	92.46
Living construction site	-	0.24	9.30	9.44	-	29.25	27.77	20.71
Traffic facility	0.50	94.81	215.60	223.47	14.83	73.81	79.86	79.83
Other land	0.98	932.61	848.52	975.42	-	192.77	210.00	268.68
Bare rock gravel land	6523.19	7128.81	7053.34	7049.77	-	-	-	-
Total	31149.44	31149.44	31149.44	31149.44	22315.15	22315.15	22315.15	22315.15

$$ASI = \frac{\sum_{i=1}^{N} SI_i A_i}{A} \tag{7}$$

$$SI_i = \frac{P_i}{2\sqrt{\pi A_i}} \tag{8}$$

$$A = \sum_{i=1}^{N} A_i \tag{9}$$

where MSI is the mean shape index of the landscape patches, and ASI is the area-weighted shape index of the landscape patches. SI_i is the shape index of landscape patch i, i.e., the ratio of the patch perimeter to the perimeter of a circle of equal area, as the shape index of a circle is 1 and the indices for other shapes are greater than 1. P_i and A_i are the perimeter and area, respectively, of patch i, and A and N are the total area and number of the landscape types, respectively.

3) FRACTIONAL VEGETATION COVER ANALYSIS

The fractional vegetation cover (FVC) refers to the percentage of the vertically projected vegetation area (including leaves, stems and branches) on the ground to the total area of the statistical area. It is an important phenotypic factor used in ecology, agriculture and forestry, as it provides a good indication of the growth of surface vegetation. The normalized difference vegetation index (NDVI) is usually employed to estimate the FVC. Green vegetation and bare soil are considered, and the pixel dichotomy model can be used to simplify the formula [37], [38]:

$$FVC = \frac{NDVI - NDVI_S}{NDVI_\infty - NDVI_S} \tag{10}$$

where $NDVI_S$ stands for the NDVI value of an image element that is entirely bare soil or without vegetation cover and $NDVI_\infty$ stands for the NDVI value of an image element that is completely covered by vegetation [39]. $NDVI_S$ and $NDVI_\infty$ are generally taken to be the maximum and minimum values within a range of confidence levels, which are mainly determined by the actual image.

The Theil-Sen median analysis was used to perform a long time-series trend analysis of the FVCs. Compared with ordinary linear regression methods, it has stronger resistance to data errors. It can reduce the influence of outliers, which improves the accuracy of the test results to a certain extent [40], [41]. It is calculated as follows:

$$\beta = Median\left(\frac{FVC_j - FVC_i}{j-i}\right), \quad \forall j > i \tag{11}$$

where β stands for the interannual variation rate of the FVCs, when $\beta > 0$, the FVC tends to increase in the time series, and when $\beta < 0$, the FVC tends to decrease. i and j represent the numbers of the time series, and FVC_i, and FVC_j represent the corresponding years of the FVC dataset.

III. RESULTS

A. SPATIOTEMPORAL CHARACTERISTICS OF LAND USE

The spatial distribution of land use in JHG and JC in 2003, 2010, 2014, and 2020 are shown in Tab. 2 and Fig. 3. The main land use type was grassland, which accounted for 71.53% of the study area (e.g., high-coverage grassland, medium-coverage grassland and low-coverage grassland accounted for 22.89%, 26.11%, and 22.53%, respectively) in 2020. The proportions of unutilized land, production and living land, water and wetland were 13.19%, 11.40%, and 3.88%, respectively.

In terms of zoning, the grassland in JHG accounted for 58.94% of the total area, while the proportion in JC was 89.11% in 2020. Fig. 3 clearly shows that the vegetation cover in JC is much higher than that in JHG because the proportion of high-coverage grassland in JC is higher. At the same time, JHG is dominated by medium-coverage grassland. The high-, middle- and low-coverage grasslands in JHG accounted for 3.89%, 56.38%, and 39.73% of the total grassland area, respectively, while in JC, they accounted for 57.96%, 18.14%, and 23.90%, respectively. The reason for the great differences in the grassland distribution between the two districts is that JHG is located at a higher altitude than JC. The high altitude is accompanied by a decrease in temperature, which is extremely unfavorable for vegetation

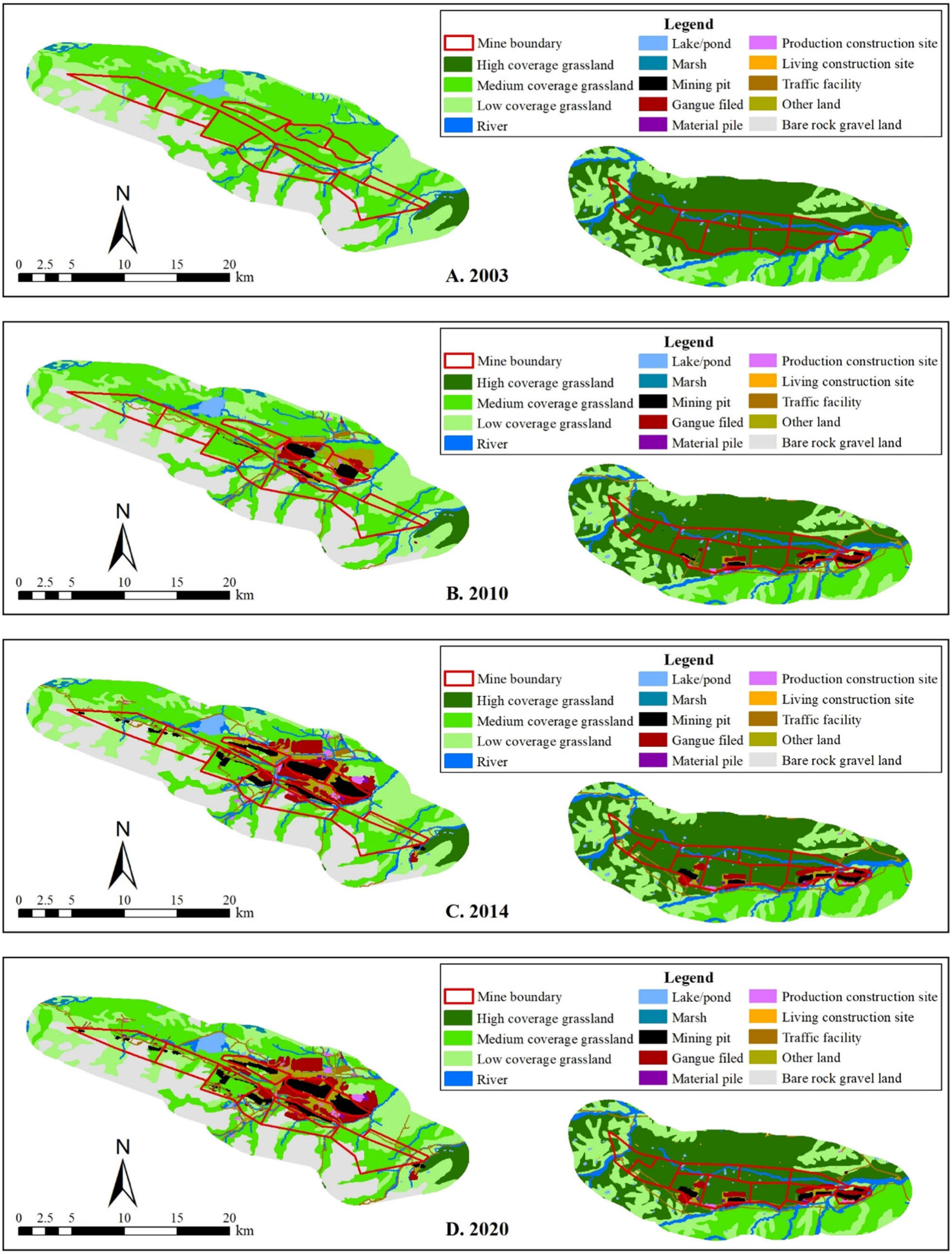

FIGURE 3. The spatiotemporal distribution of land use in the Muli coalfield in 2003, 2010,2014 and 2020.

growth, so 7094.77 hm^2 (22.63% of the total area) of the unutilized land occurs in JHG.

B. LAND USE TRANSFORMATION

1) AREA OF TRANSFER

Fig. 4 illustrates the area conversion relationship between the different land use types in the three phases in JHG and JC.

The land use transfers during the mining phase were complex in 2003-2014, with conversion relationships between multiple land use types. The largest area of land transferred out was grassland, with 3711.09 hm^2 of medium coverage grassland in JHG and 1005.63 hm^2 of high coverage grassland in JC converted to the productive and living land. The main transfer-out directions of the land types were to mining pits and gangue fields, followed by other land. The process of transferring to mining pits and gangue fields was more obvious in JHG. The amount of unutilized land in JC increased by 607.54 hm^2 during 2003-2010, and its main source was medium- and low-coverage grassland.

There was also an interconversion between grasslands of different coverages, mainly in the first mining phase. In JHG, 0.30 hm^2 (0.04%) of high coverage grassland was transferred to low coverage grassland, 96.41 hm^2 (0.78%) of medium coverage grassland was transferred to low cover grassland, and 0.71 hm^2 (0.01%) of low coverage grassland was transferred to medium coverage grassland. In JC, 24.41 hm^2 (0.21%) of high coverage grassland was transferred to low coverage grassland, 13.94 hm^2 (0.12%) of medium coverage grassland was transferred to low cover grassland, and 0.30 hm^2 (less than 0.01%) of low coverage grassland was transferred to high coverage grassland.

During the restoration phase in 2014-2020, the land use transfers tended to be stable and did not change greatly. However, transfers of grassland to mining pits and gangue fields still occurred in JHG, which directly indicated that mining activities were still ongoing in JHG during this phase.

2) NET CHANGES

Fig. 5 shows the net changes in land use types in the three phases. The characteristics of the net changes in these two districts were generally the same, with large net changes during the mining phase and small net changes during the reclamation phase. Specifically, the net decrease in grassland during the mining phase was large, and the net increases in mining pits and gangue fields were the largest, which were followed by those of other lands. The net increases for the mining pits and gangue fields in the second mining phase of JHG were much larger than those in the first mining phase, while the net increases in JC were the opposite. This result indicated that the expansion of mining activities in JC mainly occurred from 2003 to 2010 and that in JHG occurred from 2010 to 2014. It should be noted that the areas of the river and lake/pond land types decreased significantly in the second mining phase, with a decrease of 96.10 hm^2 in JHG and 63.76 hm^2 in JC.

3) LAND USE DYNAMIC DEGREE

To analyze the active degrees of land use transfer in the Muli coalfield, we calculated the LUDDs of the two districts for the three phases based on the land use dataset (Tab. 3). The basic characteristics of the LUDDs in the two districts were generally consistent, with the highest activities for productive and living land, followed by water and wetland, and the activity for grassland was relatively low.

The TLUDDs of the production and living land in JHG and JC in the first mining phase were 99.84% and 98.51%, respectively, which indicated that the changes were drastic. In addition, the LUDDs of secondary land use were all above 99% except for transportation facilities and were even as high as 100%, which indicated that these land uses newly emerged in this phase.

The TLUDDs during the two mining phases in JHG were 9.47% and 11.80% and were greater than those in JC (e.g., 4.66% and 2.84%, respectively). The intensity of the production and construction activities in JHG was greater and had a more extensive impact on the land use structure. The TLUDDs during the first phase were smaller than those during the second phase in JHG, which indicated that the land use transfers in the second phase were more active, while JC exhibited an opposite trend, which was consistent with the results of the net changes.

The LUDDs clearly decreased from 2014 to 2020, and the LUDDs of most land use types were less than 10%, except for production land. The TLUDDs in the two districts were 1.08% and 0.47%, respectively, which indicated that the land use structure was stabilizing. In this phase, the LUDDs were relatively larger for the material piles and production construction sites. Combined with the survey results, the reason for this phenomenon may be that these two types were demolished and renovated during the ecological restoration process but were not completely restored to grassland. Hence, the land use type still belonged to production land.

C. LANDSCAPE PATTERN CHANGES

The landscape PD changes over four years shown in Fig. 6 indicate that the PDs of the landscape elements exhibited large continuous changes from 2003 to 2014 and small changes from 2014 to 2020, which indicated that the landscape fragmentation in the Muli coalfield first intensified and then tended to be stable.

In terms of the overall trend, the PDs of the landscape elements in JHG ranged from 0 to 0.45/100hm^2, with significant changes in the medium- and low-cover grasslands, rivers, production construction sites, other sites and gangue fields in 2003-2014. The PDs for medium-coverage grassland ranged from 0.09/100 hm^2 to 0.31/100 hm^2, and those for low-coverage grassland ranged from 0.15/100 hm^2 to 0.39/100 hm^2. The PDs of the landscape elements in JC ranged from 0 to 0.35/100 hm^2, and the areas of low-coverage grassland and high-coverage grassland evidently increased

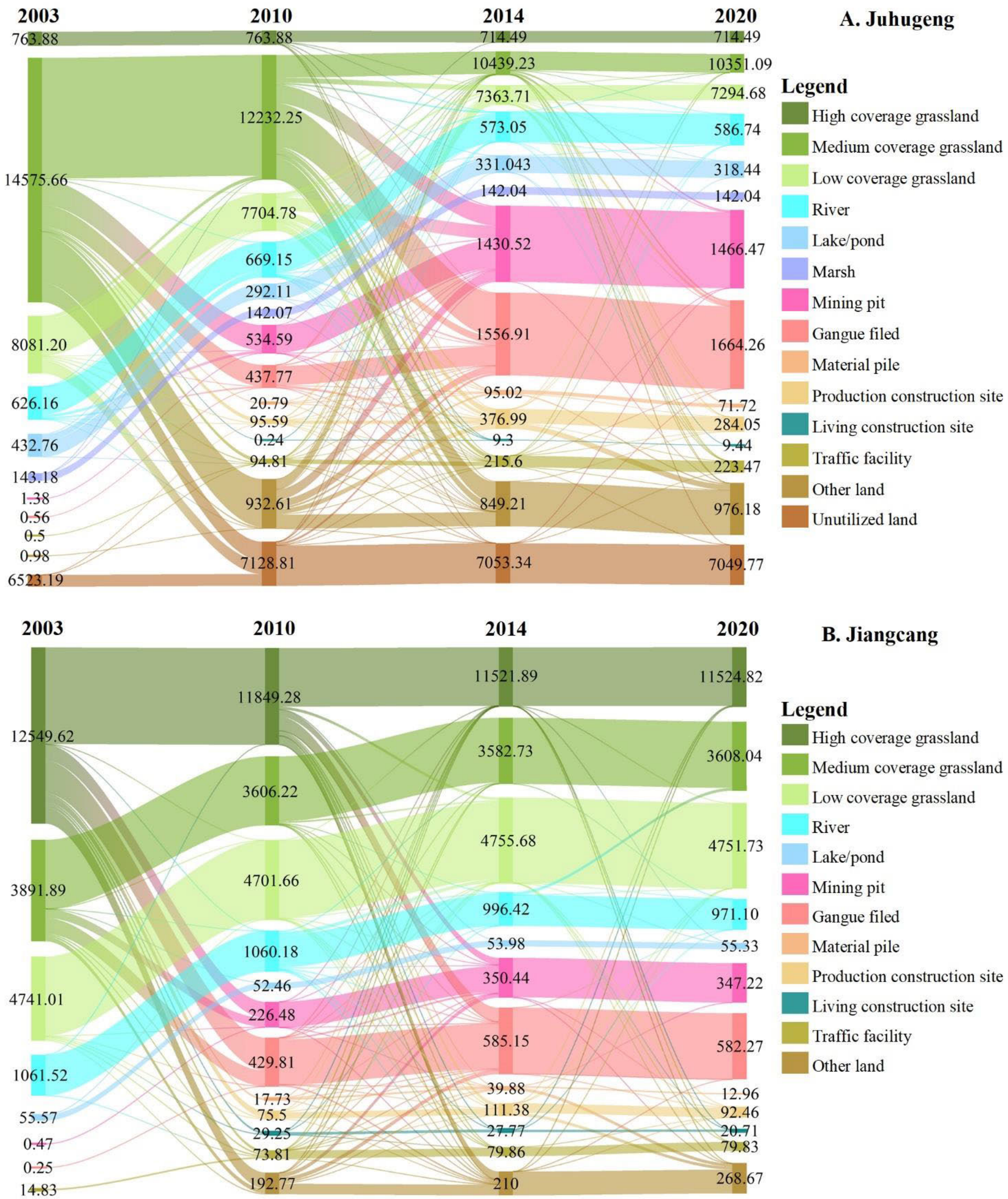

FIGURE 4. Land use transfers from 2003 to2010, 2010 to 2014, and 2014 to 2020 (unit:hm^2). The widths of the bars indicate the input/output areas for each land use type. Since the total area of grassland, bare rock and gravel land are large, and most of the area has not changed, the area of three types of grassland, bare rock and gravel land has been decreased in the figure to more clearly show the area changes of various land use types. The reduction in area is the same for all four years, and this adjustment will not affect the areas of the other transfers.

from 0.12/100 hm^2 to 0.30/100 hm^2, and from 0.04/100 hm^2 to 0.15/100 hm^2, respectively. There were no clear changes in the PDs of high-coverage grassland, lakes, and marshes in JHG and in lakes in JC.

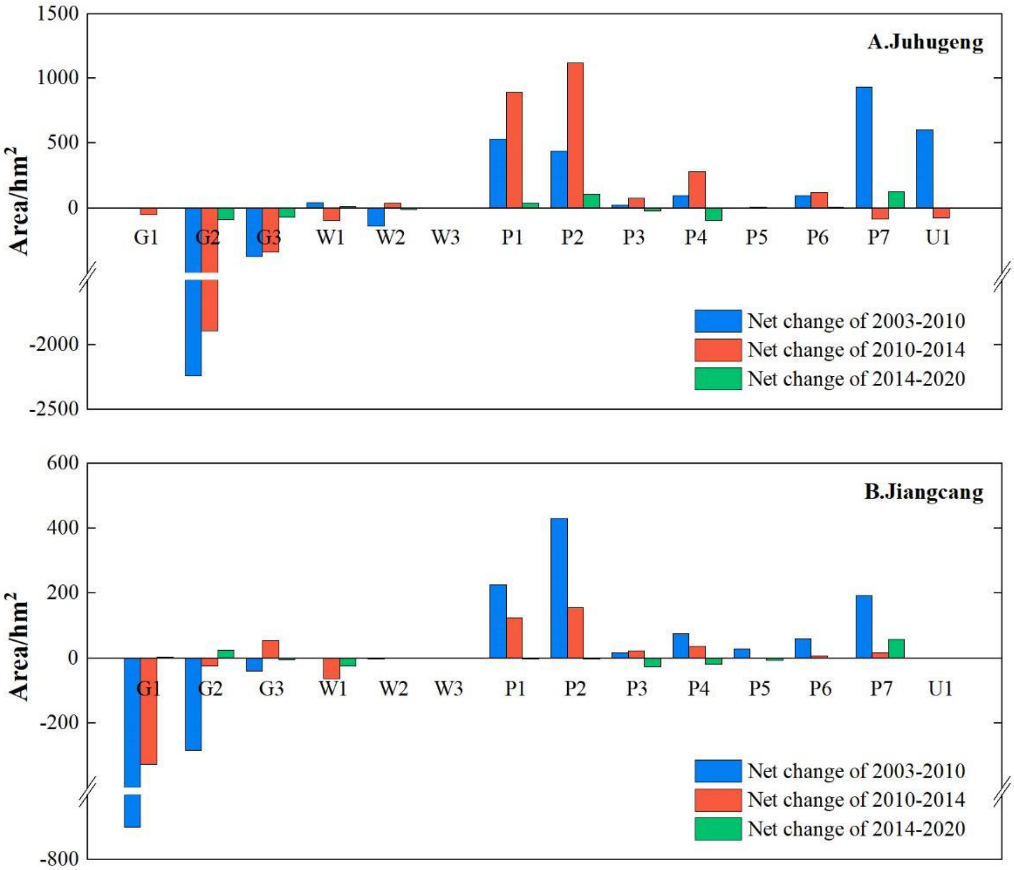

FIGURE 5. The net changes in the land use types in Juhugeng and Jiangcang. Notes: G1: High coverage grassland, G2: Medium coverage grassland, G3: Low coverage grassland, W1: River, W2: Lake/pond, W3: Marsh, P1: Mining pit, P2: Gangue field, P3: Material pile, P4: Production construction site, P5: Living construction site, P6: Traffic facility, P7: Other land, and U1: Bare rock gravel land.

TABLE 3. The LUDD of land use.

Land Use	Juhugeng			Jiangcang		
	2003-2010	2010-2014	2014-2020	2003-2010	2010-2014	2014-2020
High coverage grassland	0.00%	6.47%	0.00%	5.58%	2.89%	0.13%
Medium coverage grassland	16.29%	15.59%	0.87%	7.34%	1.32%	0.70%
Low coverage grassland	5.10%	12.24%	1.08%	1.09%	2.04%	0.13%
Grassland	11.91%	13.99%	0.92%	4.90%	2.41%	0.24%
River	31.08%	29.70%	4.03%	0.53%	8.56%	2.55%
Lake/pond	32.50%	14.18%	5.47%	8.24%	2.82%	2.42%
Marsh	0.78%	0.02%	0.00%	-	-	-
Water and wetland	28.31%	21.89%	3.95%	0.92%	8.29%	2.54%
Mining pit	99.74%	63.61%	3.09%	99.79%	36.04%	0.92%
Gangue field	99.87%	77.81%	6.45%	99.94%	35.34%	0.49%
Material pile	100.00%	88.93%	31.32%	100.00%	58.55%	67.51%
Production construction site	100.00%	87.24%	30.15%	100.00%	57.35%	28.32%
Living construction site	100.00%	98.50%	1.49%	100.00%	30.09%	30.64%
Traffic facility	99.48%	63.84%	4.92%	79.91%	17.96%	0.03%
Other land	99.90%	82.68%	14.46%	100.00%	69.69%	22.73%
Production and living land	99.84%	75.76%	9.38%	98.51%	43.65%	9.29%
Unutilized land	8.55%	1.10%	0.05%	-	-	-
Total	9.47%	11.80%	1.08%	4.66%	2.84%	0.47%

The PDs of material piles, production construction sites and living construction sites were null in 2003, and only in 2010 did small PDs begin to appear. This result indicates that these anthropogenic landscape elements newly emerged from 2003 to 2010. The emergence of these new landscape elements and their scattered distributions split the integrity of

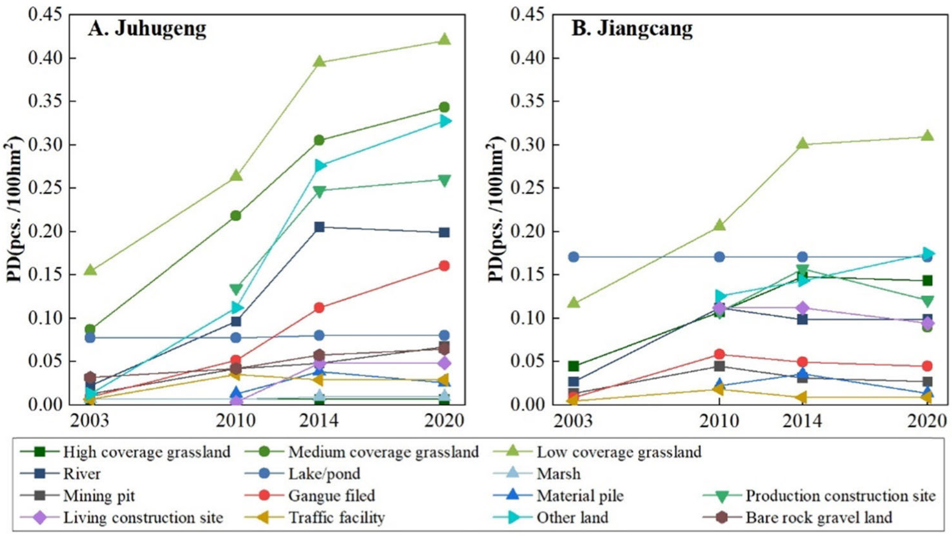

FIGURE 6. The PDs of the landscapes in Juhugeng and Jiangcang.

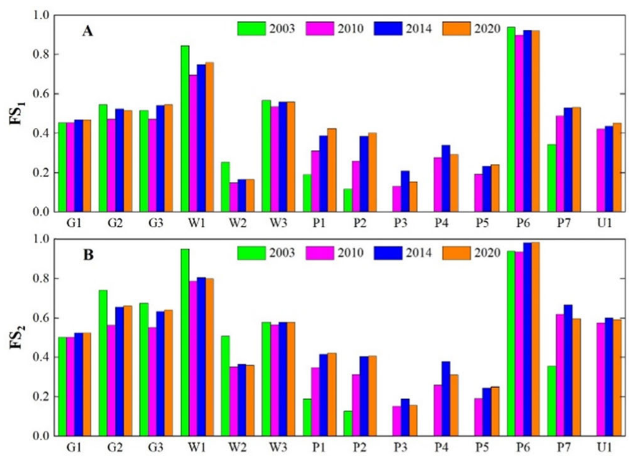

FIGURE 7. The shape fragmentation index values at the element level in Juhugeng. G1: High coverage grassland, G2: Medium coverage grassland, G3: Low coverage grassland, W1: River, W2: Lake/pond, W3: Marsh, P1: Mining pit, P2: Gangue field, P3: Material pile, P4: Production construction site, P5: Living construction site, P6: Traffic facility, P7: Other land and U1: Bare rock gravel land.

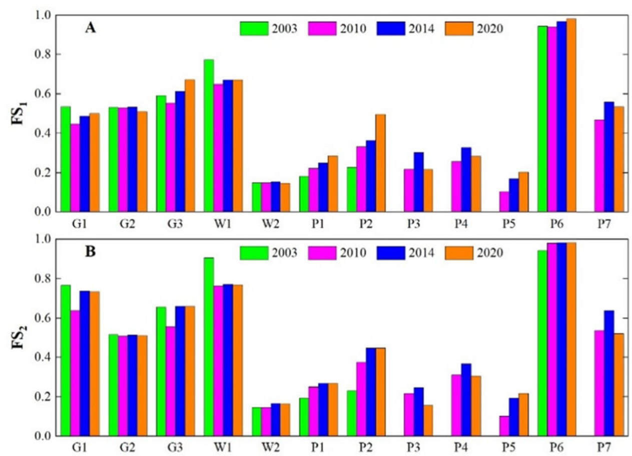

FIGURE 8. The shape fragmentation index values at the element level in Jiangcang. G1: High coverage grassland, G2: Medium coverage grassland, G3: Low coverage grassland, W1: River, W2: Lake/pond, P1: Mining pit, P2: Gangue field, P3: Material pile, P4: Production construction site, P5: Living construction site, P6: Traffic facility and P7: Other land.

the grassland landscape and increased the degree of landscape fragmentation.

According to the results of the FS$*$ values at the landscape element level (Fig. 7, Fig. 8), the FS_1 and FS_2 values of the grasslands in the two districts showed a trend of decreasing, increasing and then stabilizing in the three phases, which indicated that the FS* values for grassland changed from regular to fragmented, but the overall change was only 0.2. The changes of the FS value for the high-coverage grassland in JHG and the medium coverage grassland in JC were close to 0, so the patch shapes generally remained intact. The overall trends of FS* values for rivers and lakes were similar to that of grasslands, which decreased in 2003-2010, increased slightly in 2010-2014, and remained unchanged in 2014-2020. There were no obvious changes in the shape of the marsh patches.

The traffic facilities were stripped, and the FSs were close to 1, with a little overall variation. The rest of the productive and living lands all showed increases in their FS values to different degrees during the mining phase, which meant that the FSs of the anthropogenic landscape patches increased continuously. During the ecological restoration phase, the material piles, production construction sites and other lands exhibited decreases in their FS*values, while the others did not change significantly.

D. FVC CHANGES

We calculated the annual average FVCs from 2003 to 2020 for the gangue fields in the study area where ecological

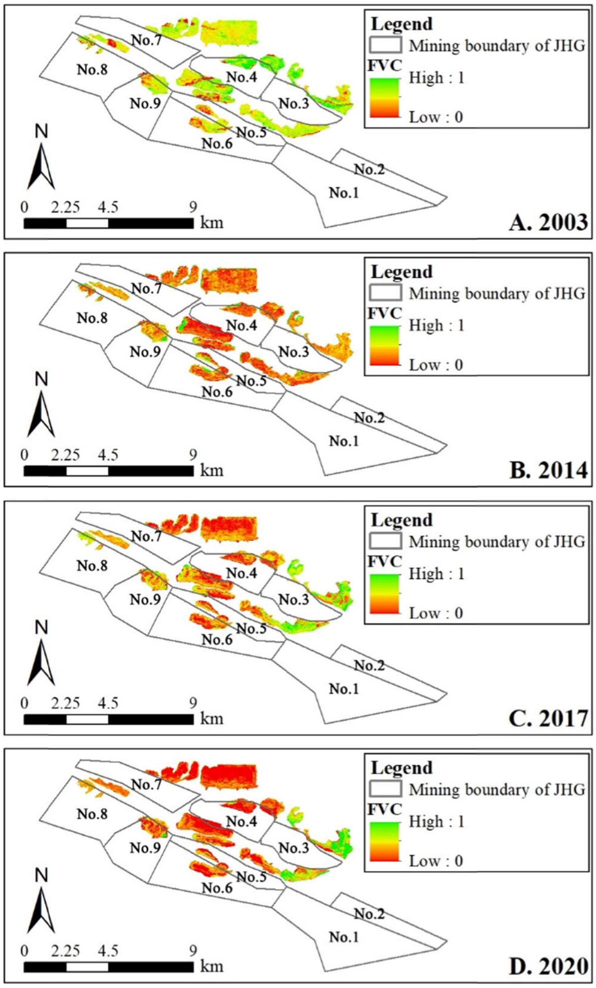

FIGURE 9. The spatial variations of FVC in Juhugeng.

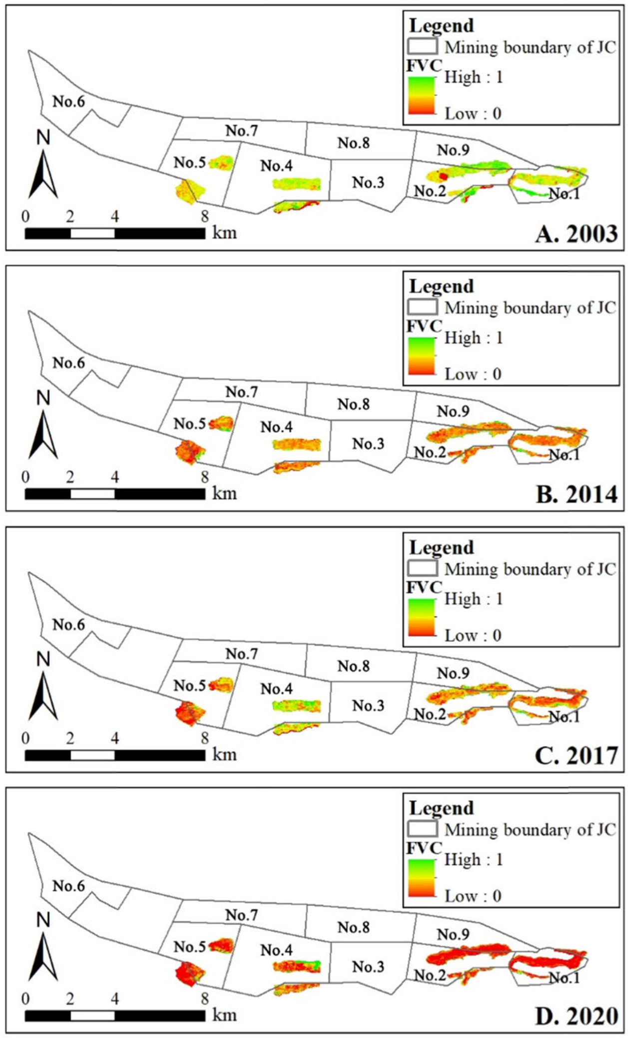

FIGURE 10. The spatial variations of FVC in Jiangcang.

restoration projects were carried out. The spatial and temporal variations in the FVCs for the two districts are shown in Fig. 9 to Fig. 11.

1) VARIATIONS IN FVC VALUES DURING THE MINING PERIOD

The FVCs clearly decreased during the mining phase (2003-2014), from 0.64 to 0.20 in JHG and from 0.67 to 0.10 in JC. In terms of spatial distributions, all of the slag hills experienced a significant decrease in vegetation cover during this phase. A sharp decline in FVCs occurred in JC in 2003-2006, while the FVCs in JHG decreased since 2006, which were consistent with when coal mining began. The slopes of the first mining phase (2003-2010) were slightly smaller than those of the second mining phase (2010-2014) in both districts because large-scale mining started after a new mining permit was obtained in 2010, which resulted in a greater decrease in FVCs.

2) VARIATIONS IN FVC VALUES DURING THE RESTORATION PERIOD

The restoration project for the gangue fields started in 2014, and by 2017, the FVCs exhibited obvious improvements, and the FVCs increased to 0.29 in JHG and 0.21 in JC. The rate of increase in JC (slope 0.040/year) was slightly greater than that of JHG (slope 0.027/year). The largest increases in FVCs occurred in JHG's No. 3 mine and No. 5 mine and JC's No. 4 mine, which were consistent with the field investigation results that indicated these two mines were the most timely and costly to restore. However, since 2017, the average FVCs began to decrease to 0.18 (slope -0.037/year) in JHG and decrease to 0.16 (slope -0.018/year) in JC. The spatial variations in the FVCs in the two districts were different. The FVC in the restored area of JHG's No. 3 mine did not decrease significantly, but the overall decrease in the other zones, while in JC, the FVCs in the restored area in the No. 4 mine decreased significantly. The decline in FVCs in the restored area of JC may be related to the restoration measures.

IV. DISCUSSION

A. THE IMPACT OF MINING ON THE ECO-ENVIRONMENT

In 2003-2014, the impacts of the surface mining activities on the ecological environment in the Muli coalfield were

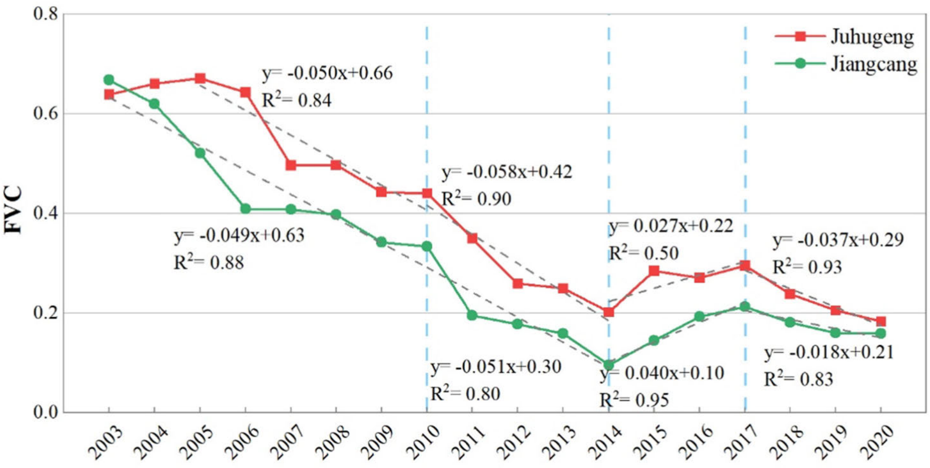

FIGURE 11. Trends of the annual average FVCs in Juhugeng and Jiangcang.

manifested as: (1) simple to complex land use structures, (2) increased landscape fragmentation, and (3) severe decreases in FVCs. The original land use structure before mining consisted mainly of grassland (83.43%), bare land (12.20%), and water (4.34%), with only small traces of human activity (0.03%). However, production and living land began to appear, which were caused by mining activities, since 2003 and sprawled rapidly with the expansion of mining to 4878.49 hm^2, while at the same time, the land use structure tended to become complicated. The land use changes from 2003 to 2014 consisted of transfers of grassland to mining pits and gangue fields, but the most transferred-out land use type in JHG was medium-coverage grassland, and the most transferred-out land use type in JC was high-coverage grassland.

The results of the land use transfers showed significant changes in the spatial distributions of rivers in 2010-2014. The river in the No. 4 mine was completely cut off owing to the expansion of mining. The No. 6 mine and No. 8 mine resulted in rivers being diverted to the southeast due to the expansion of the gangue field and mining pit, respectively (Fig. 12). The decreased water volume in the former river and surrounding wetlands caused the wet vegetation to dry up and the wetland ecosystem to degrade, which accelerated the evolution of wetland - meadow - degraded meadow - sandy grassland - sandy land. Thus, coal mining has affected the distributions of rivers and vegetation successions.

Coal mining has led to a fragmented and patchy distribution of the regional landscape. (1) The original intact landscape with alpine meadows was separated and isolated by industrial sites, gangue fields, mining pits, living sites and roads, forming a blocky, small-area isolated landscape, which damaged the integrity and continuity of the original grassland landscape structure and the unity of ecosystem function. The landscape fragmentation often limited the efficiency of ecological restoration in the later phases. (2) The patch shape fragmentation of grasslands and rivers tended to increase. Nevertheless, there was a decrease during the first stage because the original grassland and river were composed of large intact patches with multiple upward extensions, so the patch shapes were complex and irregular.

The industrial coal mining sites have caused serious damage to the alpine meadows and alpine marsh meadows. They broke the original thermal balance of the stratum, which led to changes in the upper and lower limits of the permafrost layer [42], increased surface water infiltration and lowered water table, ultimately causing a decrease in the vegetation cover of the meadows.

B. THE IMPACT OF RESTORATION ON THE ECO-ENVIRONMENT

According to the field investigation of restoration projects at the Muli coalfield, the main measures that were taken were (1) dismantling the illegally constructed production and living sites and then levelling the land, (2) backfilling the mining pits using filling materials, and (3) revegetating the gangue fields. The results of the previous section can be used to test the effectiveness of ecological restoration.

The results of the land use transformations and landscape pattern changes indicated that the areas and PD and FS values of the material piles and production construction sites decreased in 2014-2020, which indicated that the artificial construction sites were dismantled and centralized renovation during this phase, and some favorable results were obtained. The areas and landscape patterns of the mining pits did not change significantly, and this result indicated that the effect of the mining pit backfilling project was not significant. As shown in Fig. 11, the average FVCs increased from 2014 to 2020, indicating that the revegetation of gangue fields enhanced the vegetation cover. However, the overall average FVCs did not increase much, mainly because the vegetation growth capacity in the study area was extremely weak due to

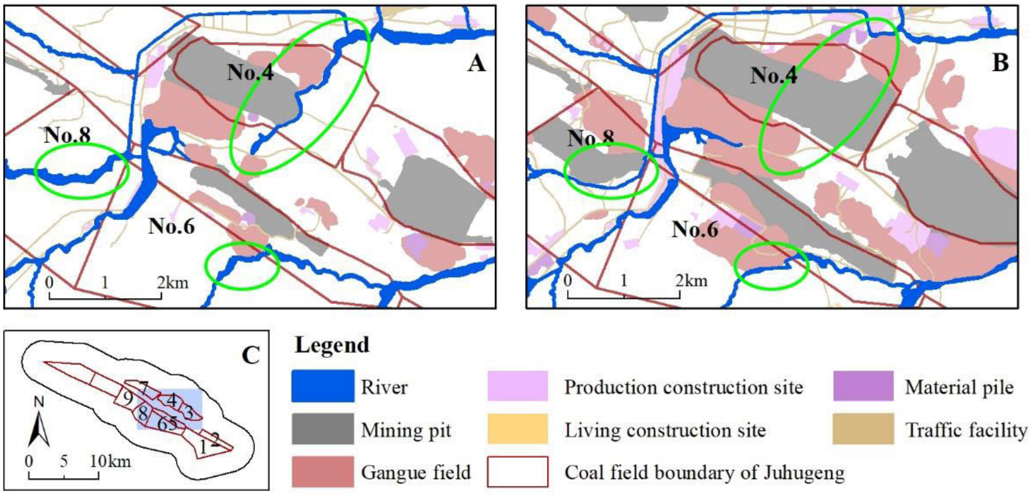

FIGURE 12. The changes in the river in Juhugeng. A and B are the distributions of the rivers in 2010 and 2014, respectively. C shows the distribution of the coal mines in Juhugeng.

the geographical location and climatic conditions. The FVCs exhibited a slowly decreasing trend after 2017, and the reason for this phenomenon may be the degradation of the reclaimed vegetation due to the decrease in precipitation, which needs further study.

The effective improvement of the FVCs from 2014 to 2017 was made possible by scientific vegetation restoration techniques. The two most critical points for maintaining vegetation cover are as follows: (1) to cover the surfaces of the gangue fields with the topsoil of certain fertility with depths greater than 10-15 cm; Because of the low temperatures and low precipitation, the nonwoven fabric was used for heat preservation and moisturizing to provide a suitable growth environment for the vegetation in the seedling stage. (2) To conduct care and management and replant in areas with poor growth and low emergence rates.

By comparing the FVC trends, we found that the increasing FVC trend in JHG (slope 0.0268/year) was smaller than in JC (slope 0.0397/year) in 2014-2017, but the decreasing trend (slope -0.0370/year) was larger than in the JC area (slope -0.0182/year) in 2017-2020. Because the average altitude is approximately 1000m higher than JC, the vegetation greening trend on the QTP is related to altitude and temperature [43], [44].

Revegetation in gangue fields had a positive impact on environmental restoration [45]. With the increased vegetation cover, the physical and chemical properties of soil [46] and the soil and water conservation capacity [47] can be improved, thus increasing the stability of the regional ecosystem [48] as well as the values of the ecosystem services [49].

C. LESSONS LEARNED

In this study, by using a remote sensing analysis of the impact of mining and restoration on the eco-environment in the mining area from 2003 to 2020 and combined with a field investigation on the restoration technology, we believed that the coal development and restoration technology in the Muli coalfield provided the following experiences and lessons to be learned:

(1) Unscientific mining methods have caused irreversible damage to mines and the surrounding environment [50]. All of the mines that were planned to use underground mining have ignored the requirements and continued to mine coal in an open-pit manner. The mining intensity is too high and exceeds the environmental carrying capacity [51].

(2) In the early stage, the overall development plan of the Muli coalfield was lacking, especially the ecological restoration plan of the mining area, and the number of mining rights in the region was unreasonable, which resulted in the discharges of gangue fields that were generated by many coal mines.

(3) Mining enterprises pursued short-term economic benefits at the expense of ecological benefits. The concept of protecting the eco-environment must be carried out during the entire cycle from geological exploration, mine design, mine production to mine closure [52]. Long-term sustainable ecological restoration can reduce the negative effects of mining on the ecosystem to a certain extent.

(4) Regarding the restoration technology, advanced methods should first be used to imitate the original natural landscape to create suitable ecological conditions at the microscopic level. Second, we should explore the vegetation restoration techniques that are adapted to local growing conditions and make optimal choices for the entire vegetation restoration process [53]–[55], including the selection of grass species, sowing methods, base soils, planting times, and covering materials, etc.

V. CONCLUSION

Based on the high-resolution remote sensing image interpretation results at four representative time points (e.g., 2003, 2010, 2014, and 2020), we obtained the spatiotemporal land use distributions for the Muli coalfield, which is the largest surface coal mine in Qinghai Province. The impacts of coal mining and ecological restoration on the eco-environment in the mining area were explored based on the changes in land use structures, landscape patterns and vegetation cover of typical regions. The four main conclusions are as follows:

(1) Large-scale uncontrolled mining in 2003-2014 caused a complex land use transfer process in the study area, which mainly resulted in the conversion of grassland to productive and living land, with alpine grassland being the largest source of transfers out (e.g., net decrease of 6225.56 hm^2) and mining pits and gangue fields being the largest direction of transfers to (e.g., net increases of 1779.11 hm^2 and 2141.24 hm^2, respectively).

(2) The landscape pattern in the study area changed significantly from 2003 to 2014. The patch densities and fragmentation levels of the grassland landscape increased owing to the expansion of the industrial landscape. The changes in the landscape indices were small, and the landscape pattern tended to be stable in 2014-2020, which indicated that small-scale ecological restoration had a minimal impact on the landscape pattern.

(3) The gangue fields that were generated due to surface mining have caused direct land occupation and have resulted in a significant decrease in vegetation cover, e.g., from 0.64 to 0.20 in JHG and from 0.67 to 0.10 in JC. The ecological restoration project has played a role in the revegetation of the gangue fields. The FVCs increased but not by much and only changed by approximately 0.1 in 2014-2017. The effectiveness of ecological restoration has subsequently declined because of factors such as climate, investments, and management efforts.

(4) Mining in ecologically fragile areas should require reasonable plans for the mining methods and scales, restore while mining, select scientific restoration technologies and adhere to long-term conservation management to achieve the sustainable development of resources and the environment.

The eco-environmental problems in the Muli coalfield of the QTP have attracted great attention in China. The results of this study can guide the ecological restoration of mining areas and provide directions for local environmental protection departments and policy-makers. Subsequent studies may begin with more detailed analyses of the ecosystem service functions by comparing the water conservation, soil conservation and biodiversity protection functions with those of the pre-mining state to improve the ecological benefits of the mine area in a more targeted way. On the other hand, more scientific and reasonable ecological restoration techniques, especially revegetation techniques, should be examined to adapt to the alpine climate of the Qinghai-Tibet Plateau.

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DONGZHU YUAN was born in 1991. She is currently pursuing the Ph.D. degree in geodetics and surveying engineering with the China University of Mining and Technology-Beijing. Her research interests include the ecological environment restoration in mining areas, and concurrent mining and reclamation.

ZHENQI HU was born in 1963. He is currently a Professor with the School of Geosciences and Surveying Engineering, China University of Mining and Technology-Beijing, and the School of Environment and Spatial Informatics, China University of Mining and Technology. He is also a specially appointed Professor of the Cheung Kong Scholar Program, and has presided over a number of projects of the National Natural Science Foundation of China. His research interests include land resource management, ecological environment restoration, and soil science.

KUN YANG is currently pursuing the Ph.D. degree in geodetics and surveying engineering with the China University of Mining and Technology-Beijing. His research interests include remote sensing and land monitoring.

GENSHENG LI is currently pursuing the Ph.D. degree in geodetics and surveying engineering with the China University of Mining and Technology. His research interests include concurrent mining and reclamation, and spatial planning.

JIAXIN GUO is currently pursuing the Ph.D. degree in land resource management with the China University of Mining and Technology-Beijing. His research interests include landscape ecology and spatial planning.

PENGYU LI is currently pursuing the Ph.D. degree in geodetics and surveying engineering with the China University of Mining and Technology-Beijing. His research interests include ground subsidence control in coal mining, and concurrent mining and reclamation.

YAOKUN FU is currently pursuing the Ph.D. degree in geodetics and surveying engineering with the China University of Mining and Technology-Beijing. His research interests include ground subsidence control in coal mining, and concurrent mining and reclamation.