Vegetation dynamics of coal mining city in an arid desert region of Northwest China from 2000 to 2019 postprint

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Abstract

Coal mining has led to serious ecological damages in arid desert region of Northwest China. However, effects of climatic factor and mining activity on vegetation dynamics and plant diversity in this region remain unknown. Wuhai City located in the arid desert region of Northwest China is an industrial city and dominated by coal mining. Based on Landsat data and field investigation in Wuhai City, we analyzed the vegetation dynamics and the relationships with climate factors, coal mining activity and ecological restoration projects from 2000 to 2019. Results showed that vegetation in Wuhai City mostly consisted of desert plants, such as Caragana microphylla, Tetraena mongolica and Achnatherum splendens. And the vegetation fractional coverage (VFC) and greenness rate of change (GRC) showed that vegetation was slightly improved during the study period. Normalized difference vegetation index (NDVI) was positively correlated with annual mean precipitation, relative humidity and annual mean temperature, indicating that these climate factors might play important roles in the improved vegetation. Vegetation coverage and plant diversity around the coal mining area were reduced by coal mining, while the implementation of ecological restoration projects improved the vegetation coverage and plant diversity. Our results suggested that vegetation in the arid desert region was mainly affected by climate factors, and the implementation of ecological restoration projects could mitigate the impacts of coal mining on vegetation and ecological environment.

Full Text

Preamble

Vegetation Dynamics of a Coal Mining City in an Arid Desert Region of Northwest China from 2000 to 2019

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Abstract: Coal mining has led to serious ecological damage in the arid desert region of Northwest China. However, the effects of climatic factors and mining activity on vegetation dynamics and plant diversity in this region remain unknown. Wuhai City, located in the arid desert region of Northwest China, is an industrial city dominated by coal mining. Based on Landsat data and field investigation in Wuhai City, we analyzed vegetation dynamics and their relationships with climate factors, coal mining activity, and ecological restoration projects from 2000 to 2019. Results showed that vegetation in Wuhai City consisted mostly of desert plants, such as *Caragana microphylla*, *Tetraena mongolica*, and *Achnatherum splendens*. The vegetation fractional coverage (VFC) and greenness rate of change (GRC) indicated that vegetation improved slightly during the study period. The normalized difference vegetation index (NDVI) was positively correlated with annual mean precipitation, relative humidity, and annual mean temperature, suggesting that these climate factors played important roles in vegetation improvement. Vegetation coverage and plant diversity around coal mining areas were reduced by mining activity, while the implementation of ecological restoration projects improved vegetation coverage and plant diversity. Our results suggest that vegetation in the arid desert region was mainly affected by climate factors, and that the implementation of ecological restoration projects could mitigate the impacts of coal mining on vegetation and the ecological environment.

Keywords: climate factor; ecological restoration; normalized difference vegetation index (NDVI); plant diversity; Wuhai City

1 Introduction

Vegetation is an important component of the global environment that affects several processes, including the terrestrial carbon cycle, energy exchange, and water balance [**?**, **?**, **?**]. Vegetation growth is affected by climate factors such as precipitation, temperature, and wind speed. Vegetation is not only sensitive to climate but also regulates climate change through geophysical and biogeochemical feedback mechanisms [**?**, **?**]. For example, Xu et al. (2018) analyzed dynamic vegetation changes in the Mu Us Sandy Land from 1981 to 2013 using remote sensing technology and landform analysis methods, finding that vegetation increase was related to reduced wind power and vegetation colonization or afforestation on bare sand dunes. Analysis of Sahel vegetation dynamics using the Global Inventory Modeling and Mapping Studies (GIMMS-3g) dataset and field investigation methods showed that increased precipitation benefited vegetation restoration during 1984–2011 [**?**, **?**]. Vegetation dynamics analyzed with Moderate Resolution Imaging Spectroradiometer (MODIS) data in the Hulun Buir meadow steppe were mainly related to temperature with no time lag, whereas the impact of precipitation was not obvious [?, ?].

In addition to climate factors, anthropogenic activities such as open-pit coal mining, overgrazing, and land use conversion from grassland to cropland have destroyed natural vegetation, leading to ecological environment degradation. For instance, natural grassland was destroyed by cultivation, grazing activities, and invasion of alien plant species [?, ?]. Mining has led to land desertification in Wuhai City, Inner Mongolia Autonomous Region, China [?, ?]. In the Yushenfu coal mine in Shaanxi, China, the area of vegetation ecological degradation caused by coal mining was 42% higher than that of unexploited areas when analyzed using normalized difference vegetation index (NDVI) data, indicating that coal mining activity had a negative impact on vegetation ecology [?, ?].

Eco-environmental projects can impact regional land use and vegetative coverage [?, ?]. Vegetation greenness increased significantly over the past 27 years in eastern and southern America due to forest management interventions [?, ?]. Vegetation area and NDVI in different climate zones of China increased by more than 50% and 40%, respectively, from 1990 to 2015 after the implementation of ecological restoration projects [?, ?]. Vegetation fractional coverage (VFC) in Inner Mongolia showed an increasing trend from 1990 to 2015. Spatially, VFC had an obvious decreasing trend from northeast to southwest in Inner Mongolia [?, ?]. VFC in Inner Mongolia gradually decreased from east to west from 1982 to 2010, and vegetation coverage was well correlated with precipitation [?, ?]. The area of reduced VFC was mainly distributed in the west of Alxa and scattered in the southern region of central Inner Mongolia from 2001 to 2010 [?, ?].

Wuhai City is an important coal production region in Inner Mongolia, China. Open-pit coal mining in this region has caused various environmental issues, such as land destruction, waste stacking, dust pollution, topsoil damage, and soil degradation [?, ?]. Vegetation was ultimately degraded and the ecological environment deteriorated [?, ?]. The deciduous shrub *Tetraena mongolica* Maxim, a protected Zygophyllaceae plant, is distributed in Wuhai City [?, ?]. Due to contamination of heavy metals molybdenum (Mo) and cobalt (Co) in soil caused by coal mining, the *T. mongolica* population decreased [?, ?]. The spatial distribution of land damage in Wuhai City featured attenuation around the mining working face, with NDVI showing a downward trend from 2000 to 2009 and then an upward trend from 2009 to 2015 [?, ?]. With continuous expansion of mining area and increasing pressure on the regional ecological environment, more attention needs to be paid to vegetation dynamics in mining areas, particularly in arid regions. Over the past 20 years, spatiotemporal changes in vegetation dynamics in the arid desert region of Northwest China have not been well discussed, particularly in Wuhai City. The interactions between vegetation coverage and climate factors or human activities in the region remain unclear, and the effect of coal mining on vegetation coverage and plant diversity at the regional scale is unknown.

This study, based on Landsat TM (Thematic Mapper) and Landsat OLI (Operational Land Imager) data combined with field surveys, analyzed vegetation dynamics and their relationships with coal mining activity and climate factors from 2000 to 2019 in Wuhai City. The aims of this study are to: (1) explore changes in vegetation dynamics in Wuhai City from 2000 to 2019; (2) analyze the relationship between vegetation and climate factors; and (3) distinguish the effects of coal mining on vegetation coverage and plant diversity. This study could provide important information for ecological restoration in coal mining areas of arid desert regions.

2.1 Study Area

Wuhai City is located in the Inner Mongolia Autonomous Region, Northwest China (39°15 -39°52 N; 106°36 -107°05 E; Fig. 1 [Figure 1: see original paper]), with a total area of approximately 1754.0 km^2. Wuhai City comprises three municipal districts: Haibowan district, Wuda district, and Hainan district, with a total population of 56.61×10^{6} in 2019. The city belongs to the arid desert region with low precipitation, high evaporation, and heavy sand-wind. The average annual precipitation ranges from 78.1 to 239.9 mm, with 90% occurring between May and September. The annual average temperature ranges from 9.2°C to 11.3°C, and the annual average relative humidity is approximately 37%-45%. The annual mean wind speed is approximately 2.3–3.1 m/s, and the annual maximum wind speed is approximately 13.6–21.0 m/s. Sandstorms are frequent in this region, with strong winds mainly originating from the northwest. Soils are mainly classified as gray desert soils and brown calcareous soils. The major vegetation types in the area include trees (*Elaeagnus angustifolia*, *Pinus*, and *Populus*), shrubs (*Artemisia ordosica*, *Haloxylon persicum*, *Caragana* spp., *Tetraena mongolica*, and *Tamarix* spp.), grasses (*Stipa bungeana*, *Poa sphondyloides*, and *Carex* spp.), and other herbs (*Agriophyllum*) [**?**, **?**].

Fig. 1 shows the location of the study area and distribution of sampling sites in Wuhai City (a, b, and c). Area M (d) is near an open-pit coal mine and includes the core reserve area (M1), reserve area (M2), and marginal area (M3) of *T. mongolica* and the open-pit coal mine (CM). BG, botanical garden; DR, dump waste reclamation area; TmD, *T. mongolica* disturbance area; W, wetland; CR, abandoned coking vegetation restoration area; SR, subsidence restoration area; NS, natural shrub vegetation area; TmN, *T. mongolica* Nature Reserve; GM, Gander Mountain.

2.2 Field Investigation

Twenty-two sampling sites in Wuhai City were selected for field vegetation investigation in June 2019. These sampling sites were divided into nine areas: *T. mongolica* Nature Reserve (TmN), *T. mongolica* disturbance area (TmD), natural shrub vegetation area (NS), Gander Mountain (GM), dump waste reclamation area (DR), abandoned coking vegetation restoration area (CR), subsidence restoration area (SR), botanical garden (BG), and wetland (W) near the Yellow River. At each sampling site, three representative parallel quadrats were established, and the latitude and longitude of the quadrats were recorded using a global positioning system (GPS). Each quadrat measured 15 m × 15 m. Vegetation indicators including coverage, height, plant density, and composition were recorded for each quadrat. Alpha diversity indices such as Simpson' s index, Shannon-Wiener' s index, and Pielou' s evenness were calculated as described in González-Hernández et al. (2020). Beta diversity represents the extent of species replacement or biotic change along an environmental gradient, and Cody' s index and Sørensen' s index of beta diversity were calculated as described in Gebrehiwot et al. (2019).

2.3.1 Data Sources

In this study, Landsat 30-m resolution data were employed and obtained from the United States Geological Survey (http://earthexplorer.usgs.gov/). A total of 13 stages of remote sensing images (Landsat TM or Landsat OLI) were selected from 2000 to 2019 (Table 1). To exclude seasonal impacts of crops within a year, this study focused on the growing season from May to August. Images with minimal clouds and shadows covering the study area were preferentially selected when possible, or their influences were minimized.

Table 1 Remote sensing images used in this study

Remote sensing type	Date (mm/dd/yy)	Remote sensing type	Date (mm/dd/yy)
Landsat TM	08/29/2000	Landsat TM	06/18/2011
Landsat TM	08/19/2002	Landsat OLI	07/28/2014
Landsat TM	08/15/2003	Landsat OLI	05/30/2016
Landsat TM	06/01/2005	Landsat OLI	05/17/2017
Landsat TM	08/14/2006	Landsat OLI	08/29/2018
Landsat TM	08/10/2007	Landsat OLI	06/19/2019
Landsat TM	06/28/2009		

2.3.2 NDVI

NDVI, calculated as the ratio of the difference between near-infrared and red visible reflectance values to their sum, is widely recognized as an effective method for studying changes in terrestrial vegetation patterns and the ability of vegetation to absorb photosynthetically active radiation [?, ?, ?]. In this study, we calculated NDVI in ENVI (Environment for Visualizing Images) v5.1 after removing the influence of clouds, atmosphere, and solar elevation angle [?, ?]. Linear regression was applied to evaluate the strength of linear trends in NDVI over time.

2.3.3 VFC

VFC is a quantitative index for measuring vegetative cover, and we calculated VFC from the NDVI image dataset using the dimidiate pixel model method. VFC is obtained as follows:

where NDVIveg is the NDVI of pure vegetation pixels; NDVIsoil is the NDVI of pure soil pixels; and VFC is the vegetation fractional coverage. Based on the NDVI cumulative frequency table, we extracted a cumulative frequency of 5% for NDVIsoil and a cumulative frequency of 95% for NDVIveg [?, ?]. The spatial distribution of VFC was then mapped across the study area.

2.3.4 Greenness Rate of Change (GRC)

GRC is defined as the slope of the smallest power-function linear regression equation for the inter-annual change in the synthetic NDVI during a given period. The least-squares method was used to simulate the temporal trends of average NDVI in the study area [?, ?]. The GRC is calculated as follows:

GRC =

where GRC is the slope of this trend line; n is the number of years involved in the calculation; i is the position of the year involved in the calculation; and NDVIi is the average NDVI value of the first i year. The result reflects the trend of annual average NDVI during the study period. When GRC > 0, NDVI values increase during the corresponding period; otherwise, NDVI values decrease (GRC < 0) or remain constant (GRC $= 0$).

2.3.5 Land Cover

Land cover information is recognized as one of the crucial data components required for many aspects of global change studies and environmental applications [?, ?]. For land cover classification, raw remote sensing top-of-atmosphere reflectance was used as the primary input data. We divided the land cover scheme of Wuhai City according to the "Land Use Status Classification" national standard (GB/T 2010-2017). Training sites with known classes were identified by field surveying, and their signatures were generated. A support vector machine (SVM) classifier was then used for supervised classification. SVM is a nonparametric supervised statistical classification technique. SVM-based techniques are quite practical for remote sensing because of their capability to produce higher classification accuracy even with limited training datasets [?, ?], and these techniques have been adopted for categorizing degraded coal mining land [?, ?]. Each pixel in the training dataset was further examined using high-resolution images in Google Earth™ and Landsat images to ensure that land cover labels were correctly assigned. In the accuracy assessment, a confusion matrix was created, which was represented by a table showing correspondence between the classification result and a reference image assigned to a particular category. Overall accuracy was then calculated as the ratio of correctly classified pixels to the total number of pixels in the confusion matrix. The Kappa coefficient was also calculated to measure agreement between classification and truth values. According to the evaluation, overall accuracy of each category classification exceeded 85%, and the Kappa coefficient was above 0.7, indicating that final classification results had acceptable accuracy and small error.

2.4 Climate Factors

Meteorological data were provided by the National Meteorological Bureau of China from 2000 to 2019, including daily data on precipitation, temperature, relative humidity, mean wind speed, and maximum wind speed observed from the meteorological station in Wuhai City. Annual precipitation (AP), annual mean temperature (MT), mean relative humidity (RH), and mean wind speed (WS) were calculated from the meteorological data. Strong wind frequency (W%) was calculated from daily wind data and represented the percentage of time during which wind speed surpassed the threshold velocity required for sand entrainment. We used 6 m/s at 10 m height as the threshold velocity in this study [**?**, **?**].

2.5 Statistical Analysis

Pearson's correlation coefficients (r) were calculated between NDVI and climatic factors to investigate possible relationships. Ordinary least squares (OLS) regression was performed to detect linear trends in NDVI and climate factors. The locally weighted scatter point smoothing (LOWESS) method was used to smooth NDVI and climatic factor data [**?**, **?**]. Slopes acquired from OLS could quantify the changing rate, while LOWESS could depict tendencies at a finer timescale.

3.1 Variations in VFC and GRC in Wuhai City

VFC ranged from 0.00 to 1.00 in Wuhai City and was divided into five levels (Table 2). The temporal and spatial distributions of VFC showed obvious heterogeneity in Wuhai City from 2000 to 2019 (Figs. 2 and 3). VFC in Wuhai City was mainly medium-high coverage (0.30–0.60) and high coverage (0.60–1.00) in 2000. From 2000 to 2009, low coverage (0.00–0.05) areas displayed an upward trend followed by a downward trend, while high coverage (0.60–1.00) areas continuously declined, indicating vegetation degradation during this period. Medium coverage (0.15–0.30) areas decreased dramatically, while high coverage (0.60–1.00) areas increased rapidly from 2009 to 2019, indicating vegetation improvement at this stage. Moreover, the area with high coverage (0.60–1.00) increased from 53.1% in 2000 to 60.9% in 2019, indicating that vegetation improved during the 19-year period. These results suggest that vegetation initially degraded and then underwent a restoration process in the region.

Table 2 Classification of vegetation fractional coverage (VFC) in Wuhai City from 2000 to 2019

Level	Value of VFC	Description
Low coverage	0.00–0.05	Moderate desertification land, rock, buildings, opencast mine, waste dump, and low-yield grassland
Medium-low coverage	0.05–0.15	Medium-low yield grassland, industrial land, and sporadic vegetation
Medium coverage	0.15–0.30	Unutilized land, medium-low yield grassland, and medium-low shrubland
Medium-high coverage	0.30–0.60	Medium-high yield grassland, medium-high shrubland, and sparse woodland
High coverage	0.60–1.00	High-yield grassland, dense shrubland, reclaimed dump, cropland, and dense woodland

Fig. 2 [Figure 2: see original paper] shows the spatiotemporal distribution of vegetation fractional coverage (VFC) in Wuhai City for (a) 2000, (b) 2006, (c) 2009, (d) 2011, and (e) 2019. Fig. 3 [Figure 3: see original paper] illustrates area changes in VFC in Wuhai City from 2000 to 2019.

We divided GRC into six categories based on the magnitude of change ($P < 0.05$; Table 3). Areas of moderate degradation (-0.10 to -0.05) and slight degradation (-0.05 to 0.00) accounted for 54.73% and 35.99% of the total area in Wuhai City, respectively, indicating vegetation degradation from 2000 to 2009. The area of moderate improvement (0.05–0.10) accounted for 83.10% of the total area, indicating vegetation improvement from 2009 to 2019. The slight improvement area (0.00–0.05) accounted for 89.68% of the total area from 2000 to 2019, and the area of vegetation improvement was larger than that of degradation, indicating that overall vegetation generally improved during the 19-year period.

3.2 Land Cover in Wuhai City

Land cover in Wuhai City was classified into ten categories (Fig. 4 [Figure 4: see original paper]). The main water body area covered a branch of the Yellow River surrounded by wetland and cropland. Residential land was mainly distributed in the middle of Haibowan district. Coal mining areas were mainly distributed in the eastern and western parts of Wuhai City, while industrial land was mainly distributed around the coal mining area. Woodland was mainly distributed in Gander Mountain. Grassland and shrubland were dispersedly distributed throughout the entire region. Barren land was sporadically found in the industrial area and around coal mining areas.

Table 3 Dynamics of greenness rate of change (GRC) during three stages in Wuhai City

Value of GRC	Category	Area (km^2)	Percentage of total area (%)
< -0.10	Severe degradation		
-0.10 to -0.05	Moderate degradation		
-0.05 to 0.00	Slight degradation		
0.00 to 0.05	Slight improvement		
0.05 to 0.10	Moderate improvement		
> 0.10	Significant improvement		

Fig. 4 [Figure 4: see original paper] shows the dynamics of annual land cover classification in Wuhai City for (a) 2000, (b) 2006, (c) 2009, (d) 2011, and (e) 2019.

The areas of water body, residential land, industrial land, and coal mining area in Wuhai City significantly increased during the 19-year period, accounting for 3.7%, 11.4%, 2.9%, and 10.6% in 2019, respectively (Fig. 5 [Figure 5: see original paper]). Water body area dramatically increased after completion of the Wuhai Lake project in 2013 and encroached on areas of barren land, grassland, and shrubland thereafter. Increases in residential land, industrial land, and coal mining areas were roughly in accordance with the rise in raw coal production after 2006 (Fig. 5). Areas of grassland and shrubland were occupied by residential land, industrial land, and coal mining, and vegetation in coal mining areas degraded from shrubland to barren land. Areas of cropland and wetland remained relatively stable, likely due to the "cropland and wetland protection" policies of the Chinese government. Barren land area tended to expand first and then decrease, while shrubland area decreased first and then expanded moderately, and grassland area markedly decreased after 2010. Afforestation and ecological restoration programs were implemented in mining areas, such as backfilling of open-pit coal mines and reclamation of waste dumps, resulting in shrubland area improvement after 2010.

3.3 VFC in the Coal Mining Area

VFC in Wuhai City decreased first and then increased from 2000 to 2019 (Fig. 6a [Figure 6: see original paper]), and the trend of VFC in area M (Fig. 1d) aligned with that of Wuhai City (Fig. 6a). VFC increased with distance from the open-pit coal mine (Fig. 6b). In 2000, VFC in area M revealed that medium-high coverage (0.30–0.60) and high coverage (0.60–1.00) were dominant, accounting for 20%–50% and 50%–80%, respectively (Fig. 6c). The area of low coverage (0.00–0.05) in M3 and CM plots gradually increased from 2000 to 2018, while the area of high coverage (0.60–1.00) in M1 and M2 plots reached 98%, indicating that coal mining destroyed the land surface structure and dump waste occupied the *T. mongolica* area. Vegetation showed degradation in open-pit coal mines and surrounding areas during this period. The closer a plot was to the mine area, the lower the vegetation coverage and the more severe the impact of coal mining activity on vegetation.

3.4 NDVI at Different Sampling Sites

To reveal vegetation dynamics in Wuhai City from 2000 to 2019, we analyzed NDVI at nine sampling sites (Fig. 7 [Figure 7: see original paper]). NDVI in NS increased over two decades, providing evidence for the influence of climate factors on vegetation in the region. BG was built in 2003, vegetation in SR was restored with trees and shrubs from 2006, and greening plants were irrigated by drip irrigation systems at both sites, resulting in the highest NDVI values. NDVI in GM gradually increased under the influence of recent afforestation. TmN and W areas are located in nature reserves, and their NDVI was higher than that in NS. TmD was closest to the open-pit mine, and its NDVI was lower than that in TmN, indicating that vegetation was severely reduced by coal mining activity. NDVI in CR and DR was lower than that in TmN, suggesting that vegetation was destroyed by coal exploitation. Coal mining activity aggravated vegetation degradation, while waste dump reclamation and vegetation restoration in mining areas had the potential to improve vegetation coverage.

3.5 Plant Community Structure

Plant community composition, coverage, and plant diversity determined by field survey are shown in Table 4 and Figure 8 [Figure 8: see original paper]. The VFC value estimated by remote sensing analysis was highly correlated with vegetation coverage measured by field survey (the coefficient of determination reached 0.83; data not shown), indicating that VFC is a reliable indicator for evaluating changes in vegetation coverage at the regional scale. According to 2019 field survey data, vegetation in Wuhai City was mainly composed of arid desert plants such as *Tetraena mongolica*, *Caragana microphylla*, *Salsola passerina*, *Zygophyllum xanthoxylon*, and *Achnatherum splendens* (Table 4). *Tetraena mongolica* and *Reaumuria soongarica* were the dominant species in TmN. The number of *T. mongolica* decreased in TmD, while the number of *Caragana* *microphylla* and *Zygophyllum xanthoxylon* increased. Vegetation in GM was restored with trees in 2009 and dominated by *Picea asperata* and *Pinus sylvestris*, while *Populus* and *Pinus sylvestris* were dominant in the coal mining SR area. The number of *T. mongolica* was highest in TmN, followed by TmD, GM, and NS2. However, *T. mongolica* was hardly found in BG, CR, and DR (Fig. 8a), suggesting that native *T. mongolica* populations were damaged during coal exploitation and were difficult to restore under natural conditions. Vegetation coverage in TmN was higher than that in TmD, indicating that vegetation coverage was reduced by coal mining. DR had been restored by shrub species for 3–5 years, and vegetation coverage was higher than that in TmD. Vegetation restoration in CR began in 2014 with tree and shrub species, and vegetation coverage was similar to that in TmD. Vegetation greening through afforestation with trees in SR over 10 years resulted in coverage higher than at other sites. Therefore, artificial restoration could increase vegetation coverage in coal mining areas.

Table 4 Plant community composition at each sampling site

Sampling site	Species number	Dominant species
BG		*Elaeagnus angustifolia*; *Populus alba* var. *pyramidalis*; *Platycladus orientalis*
SR		*Populus alba* var. *pyramidalis*; *Amorpha fruticosa*; *Cynanchum chinense*
CR		*Pinus sylvestris* var. *mongolica*; *Picea asperata*; *Ulmus pumila*
DR		*Elaeagnus angustifolia*; *Syringa vulgaris*; *Amorpha fruticosa*
TmD		*Medicago sativa*; *Limonium bicolor*; *Amorpha fruticosa*
NS1		*Artemisia salsoloides*; *Medicago sativa*; *Alhagi camelorum*
NS2		*Achnatherum splendens*; *Tetraena mongolica*; *Convolvulus tragacanthoides*

Sampling site	Species number	Dominant species
GM1		*Artemisia salsoloides*; *Convolvulus tragacanthoides*; *Achnatherum splendens*
GM2		*Caragana microphylla*; *Cynanchum hancockianum*; *Achnatherum splendens*
TmN1		*Tetraena mongolica*; *Zygophyllum xanthoxylon*; *Achnatherum splendens*
TmN2		*Tetraena mongolica*; *Zygophyllum xanthoxylon*; *Achnatherum splendens*
TmN3		*Tetraena mongolica*; *Salsola passerina*; *Achnatherum splendens*
W1		*Achnatherum splendens*; *Ammopiptanthus mongolicus*; *Caragana microphylla*
W2		*Zygophyllum xanthoxylon*; *Nitraria sibirica*; *Cynanchum chinense*
W3		*Caragana microphylla*; *Picea asperata*; *Pinus sylvestris* var. *mongolica*
W4		*Caragana microphylla*; *Picea asperata*; *Pinus sylvestris* var. *mongolica*
W5		*Tetraena mongolica*; *Achnatherum splendens*; *Reaumuria soongarica*
W6		*Tetraena mongolica*; *Achnatherum splendens*; *Reaumuria soongarica*
W7		*Phragmites australis*; *Sophora alopecuroides*; *Tamarix chinensis*
W8		*Phragmites australis*; *Echinochloa crusgalli*; *Tamarix chinensis*

Note: BG, botanical garden; SR, subsidence restoration area; CR, abandoned coking plant restoration area; DR, dump waste reclamation area; TmD, *T. mongolica* disturbance area; NS, natural shrub vegetation area; GM, Gander Mountain; TmN, *T. mongolica* Nature Reserve; W, wetland.

Shannon-Wiener's index and Simpson's index among sampling sites from low to high followed the order TmD < NS < GM < W < TmN < BG, indicating that species diversity in TmD was severely reduced by coal mining. The restoration age in CR and DR sites was shorter than that in SR, and plant diversity and coverage in CR and DR were correspondingly lower than in SR. Pielou's indices in SR and TmN were nearly the same, but the dominant species were different. Cody's index increased from BG to DR (Fig. 8b), indicating high rates of species replacement in coal mining restoration areas. The highest variation in Sørensen's index occurred between DR and NS sites, confirming dissimilarity in plant communities between *T. mongolica* areas and restored areas (SR, DR, and CR). Furthermore, the closer to the coal mining area, the lower the coverage and plant diversity. These results suggest that ecological restoration projects may play important roles in accelerating ecological restoration and reducing the impact of coal mining on vegetation.

3.6 Effects of Climatic Factors on NDVI

From 2000 to 2019, NDVI in Wuhai City displayed a decreasing then increasing tendency (Fig. 9a [Figure 9: see original paper]). Annual precipitation was about 199.1 mm and did not change significantly (Fig. 9b), while relative humidity showed an increasing linear trend at a rate of 0.229%/a (Fig. 9c), indicating that the ecological environment was improving. Mean temperature first declined then slightly increased, with an overall negative linear trend at a rate of -0.042°C/a (Fig. 9d). Strong wind frequency and wind speed declined significantly at rates of -0.018%/a and -0.032 m/(s・a), respectively (Figs. 9e and 9f), indicating that wind erosion risk in the study area had decreased during the 19-year period. Overall, NDVI was positively related to RH (r = 0.49, P = 0.001), while NDVI was negatively correlated with W% (r = -0.67, P = 0.012) and WS (r = -0.32, P = 0.007), suggesting that relative humidity and wind speed were important climate factors affecting vegetation activity in the region.

4.1 Effects of Climate Factors on Vegetation Dynamics

Wuhai City is a typical arid desert region where vegetation is sensitive to climate change. Precipitation was the primary climatic factor controlling vegetation growth in this region. NDVI gradually decreased from northeast to southwest in Inner Mongolia, showing an evident transition phenomenon between dry and wet areas [**?**, **?**]. NDVI was reduced to 0.20–0.40 in the semi-arid steppe area in the central region, indicating that vegetation in this area is gradually becoming sparser. In the arid desert region of western Inner Mongolia, NDVI is less than 0.10, with the surface mainly covered by desert, gobi, bare soil, and bare rock [**?**, **?**]. Our results showed that annual precipitation in Wuhai City fluctuated around 199.1 mm during the 19-year period, and the average NDVI of Wuhai City was less than 0.05, indicating that overall vegetation coverage was low and related to lower precipitation. Precipitation most strongly and significantly limited vegetation growth over 45.1% of Inner Mongolia, while air temperature significantly limited vegetation growth over only 0.73% in a small part of northeastern Inner Mongolia [?, ?]. In Wuhai City, mean temperature increased after 2012, and relative humidity displayed an increasing trend though annual precipitation did not change during the 19-year period. In fact, construction of Wuhai Lake was completed in 2013, and the water body area reached 118.0 km^2. Drip irrigation facilities were established in plantation-style forests (GM) and shrubland in remediation sites (DR). Thus, the increased relative humidity might be related to the extended water area and elevated soil water content caused by artificial irrigation. We infer that the Yellow River Water Conservancy Program (2010) in Wuhai City may have played an important role in improving air humidity. NDVI was positively related to relative humidity, indicating that plant growth was mainly improved by soil water and relative humidity in 2012. Soil losses caused by wind erosion decreased vegetation coverage and aggravated sand mobilization in the Sahel [?, ?]. Less wind could reduce the potential for surface erosion and sand transportation and contributed to vegetation growth and stability in the Mu Us Sandy Land [?, ?]. In Wuhai City, the reduction in wind speed and increase in relative humidity over the 19-year period indicate that the regional ecological environment was gradually improving.

4.2 Effects of Coal Mining Activity and Ecological Restoration Projects on Vegetation Dynamics

Climate change was an important factor influencing vegetation in Wuhai City. However, anthropogenic activity was also an important driving factor. The dominant species *T. mongolica* in Wuhai City significantly decreased with strengthening human disturbance from 1977 to 2005, including mining, coking, road construction, firewood cutting, and overgrazing [?, ?]. *T. mongolica* population size and density were reduced dramatically by coal mining [?, ?]. From 2000 to 2009, VFC declined (Fig. 2), with GRC < 0 (Table 3), and vegetation was seriously degraded, especially in coal mining areas (Fig. 7). One potential explanation is that vegetation growth was inhibited by low precipitation and temperature during this period (Fig. 9), while another is that vegetation was destroyed by increasing industrial land and coal mining activity (Figs. 4 and 5). From 2009 to 2019, VFC in Wuhai City increased, with GRC > 0, and vegetation showed an upward trend, particularly in coal mining areas (Fig. 7). Further, vegetation coverage trends showed diversity at local and regional scales, and different land use types exhibited different changes in vegetation coverage (Fig. 7), indicating that meteorological factors and anthropogenic activities might act together to affect spatiotemporal changes in vegetation coverage. Our field investigation found that the number of *T. mongolica*, vegetation coverage, and plant diversity in coal mining areas decreased compared with those in the *T. mongolica* Nature Reserve. The closer a site was to the coal mining area, the lower the plant diversity. This could be caused by land occupation and heavy metal contamination in the soil [?, ?].

Facing vegetation degradation and land desertification, a series of national ecological restoration projects were implemented to restore degraded ecosystems in Wuhai City, including the Beijing–Tianjin Wind/Sand Source Control Program (2000), the fourth phase of the Three-North Shelterbelt Development Project (2001), the Grain for Green project (2001), the Wildlife Protection and Nature Reserve Development Program (2001), and the Grazing Ban (2003). Based on these projects, the government established the West Erdos Natural Reserve to conserve *T. mongolica* with an area of 139.1 km^2 in Wuhai City. NDVI in the TmN area gradually increased (Fig. 7), and shrubland area in Wuhai City increased after 2008 (Fig. 5). Afforestation practice was initiated on barren mountains and SR1 of Wuhai City in 2006, with a greening area covering over 3.3 km^2. BG was constructed in 2003, covering an area of 1.4 km^2 with 1.1 km^2 of green land. Meanwhile, construction of the Gandel Mountain Ecological Civilization Scenic Spot was initiated, and 6.7 km^2 of mountain afforestation (GM) was completed in 2009. Barren land area had been reduced since 2006 (Fig. 5), and NDVI in the study area had increased since 2009 (Fig. 2). Thus, greening increased vegetation coverage and could further reverse land desertification. Evident land greening phenomena in sand and desert areas of China’ s Loess Plateau (including Wuhai City) were observed during 2006–2008, and NDVI rapidly increased during 2011–2015 [?, ?]. NDVI also significantly increased in Inner Mongolia from 2000 to 2012 [?, ?]. In addition, China’ s greening was attributed to large-scale tree plantations in low-productivity areas from 2000 to 2017 [?, ?]. These previous studies coincide with our results.

Moreover, Wuhai City implemented several ecological construction policies and projects to improve the ecological environment in coal mining areas, such as the Opinions on Strengthening the Supervision and Administration of Mineral Resource Development project (2008), the Ecological Construction project (2012), and the Comprehensive Environmental Treatment project (2014). Accordingly, revegetation in waste dumps was restored with native shrub and herb species in 2014. Roads in coal mining areas and abandoned coking plant sites were afforested with tree and shrub patterns. Consequently, NDVI in coal mining areas showed significant improvement in recent years (Fig. 7). Revegetation of waste dumps also occurred in open-pit coal mining areas in recent decades, and vegetation coverage has reached more than 90% [?, ?]. Therefore, vegetation restoration also greatly improved the ecological environment at the regional scale. Overall, NDVI in Wuhai City showed a consistent increasing trend in recent years, while potential degradation risks still existed in parts of coal mining areas. Anthropogenic impacts superimposed on long-term climate-driven variations are also significant for vegetation restoration at both local and regional scales [?, ?]. However, the contribution of human activities to vegetation greening was not yet quantitatively assessed in this region. Therefore, plant diversity and community structure in restoration areas need further examination, and ecological restoration projects should fully consider regional resource endowments and environmental carrying capacity.

5 Conclusions

We revealed vegetation dynamics in Wuhai City, an arid desert region, based on Landsat satellite remote sensing data and field surveys. Vegetation in Wuhai City mainly consisted of desert plant species such as *Caragana microphylla*, *Tetraena mongolica*, and *Achnatherum splendens*. From 2000 to 2009, vegetation degradation in Wuhai City was induced by both climate factors and coal mining activity, with climate factors likely being the main drivers and coal mining accelerating vegetation degradation. From 2009 to 2019, vegetation increase was attributed to the implementation of ecological restoration projects and improvement of the ecological environment. Overall, climate was the main driver of vegetation dynamics, coal mining affected vegetation coverage and plant diversity, while ecological restoration policies and projects played important roles in vegetation restoration. This study provides a reference for ecological restoration in arid desert regions.

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