Postprint of Spatiotemporal Evolution of Fractional Vegetation Cover in the Alhagi sparsifolia Reserve of the Turpan Basin

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Abstract

Based on Landsat TM/ETM+/OLI imagery and UAV imagery, this study established the relationship between the Normalized Difference Vegetation Index (NDVI) and vegetation coverage, calculated the parameter values of the pixel dichotomy model, retrieved the vegetation coverage of the Turpan Alhagi sparsifolia protection zone from 1996 to 2020, and investigated the spatiotemporal evolution characteristics of vegetation coverage in the protection zone over the years using simple linear regression analysis. The results indicate that over the past 25 years, the vegetation coverage of the Alhagi sparsifolia protection zone has exhibited an overall increasing trend, with the area of significant improvement accounting for 20.14% and vegetation coverage increasing from 3.09% to 18.30%. These improvements were mainly distributed along the terminal reaches of the Baiyang River from west to central areas, as well as near residential land in the western and northeastern regions. The research findings can provide scientific reference for determining parameter values of the pixel dichotomy model and offer a scientific basis for ecological environment management and protection in the Turpan Basin.

Full Text

Abstract

Based on Landsat TM/ETM+/OLI imagery and unmanned aerial vehicle (UAV) data, this study established a relationship between the Normalized Difference Vegetation Index (NDVI) and fractional vegetation coverage (FVC) to calculate parameter values for the pixel binary model and retrieve vegetation coverage in the Alhagi sparsifolia Reserve in the Turpan Basin. Linear regression analysis was then employed to investigate spatiotemporal evolution characteristics of vegetation coverage from 1996 to 2020. The results indicate that vegetation coverage in the reserve has exhibited an overall increasing trend over the past 25 years. The significantly improved area accounts for 20.14% of the total reserve area, with vegetation coverage increasing from 3.09% to 18.30%. These improvement zones are primarily distributed along the Baiyang River terminal from west to central areas and near residential land in the western and northeastern parts of the reserve. These findings provide a scientific reference for determining pixel binary model parameters and offer an evidence-based foundation for ecological restoration and conservation efforts in the Turpan Basin.

Keywords: pixel binary model; NDVI; fractional vegetation coverage; UAV remote sensing; Alhagi sparsifolia Reserve; Turpan; Xinjiang

1 Introduction

The Turpan Basin represents a typical arid region in China, with average annual precipitation of only 10–26 mm and potential evaporation approximately 200 times greater than precipitation. Most precipitation is consumed by evaporation, and desertification has historically shown an expanding trend. *Alhagi sparsifolia*, a perennial herb with deep root systems, exhibits strong vitality and tolerance to saline-alkali conditions and drought, serving as a critical barrier against wind and sand intrusion. In 2017, the world's largest single-species wild *A. sparsifolia* protection base was established in the Turpan Basin. Analyzing temporal changes and spatial trends in vegetation coverage within this reserve provides valuable insights for regional ecological restoration.

Fractional vegetation coverage (FVC) is a key indicator for evaluating ecological restoration, with measurement approaches 主要包括 field surveys and remote sensing techniques. While field measurements offer high accuracy, they are time-consuming and labor-intensive, providing only small-scale information. Remote sensing methods provide macroscopic, timely data that are relatively easy to obtain. Common approaches include empirical models, vegetation index methods, mixed-pixel decomposition models, and spectral gradient difference methods, with the pixel binary model being most widely used.

The pixel binary model assumes that information received by remote sensors consists of two components: vegetation and soil. By applying linear stretching to adjustment factors, the model mitigates effects from atmospheric conditions, soil background, and vegetation types. The model calculates FVC using the formula:

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}}$$

where $NDVI_{veg}$ represents the NDVI value for pure vegetation pixels and $NDVI_{soil}$ represents the NDVI value for pure bare soil pixels. Model accuracy depends critically on determining these two parameters. Most scholars use frequency accumulation curves to determine parameter values, but in northwest China's arid regions, extensive desert and bare soil areas exhibit relatively high NDVI values. This leads to underestimation of $NDVI_{soil}$ using frequency accumulation methods, resulting in overestimated vegetation coverage. Consequently, the cumulative frequency method is unsuitable for sparse vegetation areas, and accurately obtaining pixel binary model parameters remains a technical challenge for estimating sparse vegetation coverage.

Qin Zhihao et al. proposed using average NDVI values from clearly dense vegetation areas and obviously bare soil areas for estimation. He et al. combined land use classification maps to extract maximum and minimum NDVI values from areas without water bodies or snow cover. UAV remote sensing, as an emerging observation technology in ecological research, compensates for limitations in spaceborne and airborne remote sensing regarding resolution, revisit cycles, cloud interference, and cost. UAVs equipped with visible light sensors enable low-altitude photography that quickly and accurately identifies green vegetation areas, reducing field workload and minimizing area measurement errors compared to manual surveys. In recent years, UAV remote sensing has been applied to population distribution studies, dynamic monitoring, and crop biomass estimation, with increasing research on field quadrat surveys and vegetation index-based FVC calculations.

This study extracts NDVI from Landsat TM/ETM+/OLI imagery, establishes a relationship curve with FVC obtained from low-altitude UAV remote sensing, determines pixel binary model parameters, retrieves historical vegetation coverage in the *A. sparsifolia* reserve, and analyzes spatiotemporal variation characteristics to provide a basis for future ecological protection and improvement in the Turpan Basin.

1.1 Study Area

The *A. sparsifolia* Reserve was established in 2017, located between 88°43 –88°46 E and 42°32 –42°55 N, covering an area of 1.07\$×10^{3}\$ km^{2}. Situated in the heart of the Turpan Basin, it lies southwest of Guolebuyi Township in Toksun County, southeast of Dikaner Township in Shanshan County, and adjacent to Aiding Lake—the lowest point in the basin. The Turpan Basin is surrounded by mountains with a concave terrain. Strong solar radiation rapidly heats the surface, and heat dissipation is difficult due to the influence of the Tarim thermal low-pressure system, resulting in long hot periods. Annual rainfall is only 10–26 mm while evaporation reaches 3000 mm. The extreme maximum temperature reaches 49.6°C, with ground surface temperatures up to 76.6°C and maximum wind speeds of 40 m $\cdot$ s^{-1}, creating an extremely arid climate.

1.2 Data Sources

1.2.1 Remote Sensing Data

Landsat TM/ETM+/OLI imagery was acquired from the Geospatial Data Cloud (http://www.gscloud.cn/) and NASA's official website (http://glovis.usgs.gov/). Images from July to September (peak growing season) between 1996 and 2020 with minimal cloud cover were selected. After radiometric calibration and atmospheric correction using ENVI 5.3, the imagery was clipped using the reserve boundary vector map to calculate NDVI.

1.2.2 UAV Data

In early August 2019, UAV photography of typical vegetation quadrats was conducted in the reserve. Based on vegetation distribution patterns and road accessibility, sample plots representing low, medium, and high vegetation coverage were established [Figure 1: see original paper]. A DJI Phantom 4 RTK equipped with a visible light sensor was used for aerial photography at 100 m altitude, with coverage exceeding the quadrat boundaries to facilitate preprocessing. A total of 15 UAV images were obtained. From these images, 150 sample points were extracted. The Excess Green minus Excess Red (ExG-ExR) index with a threshold of 0 was used to generate binary images separating vegetation from background. ArcGIS zonal statistics were then applied to calculate vegetation coverage.

1.3 Methods

1.3.1 Accuracy Assessment

The Kappa coefficient is widely used for evaluating consistency in classification and rating data, applicable to unordered categorical data. A confusion matrix was established between visual interpretation results and binary classification results from UAV imagery, yielding a Kappa coefficient of 0.92 and overall classification accuracy of 98.6%, indicating high reliability.

1.3.2 Pixel Binary Model Based on NDVI

NDVI effectively indicates vegetation growth status and spatial distribution. The pixel binary model converts NDVI to FVC, overcoming limitations from soil background and atmospheric effects. The formula is:

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}}$$

where FVC and $NDVI$ represent fractional vegetation coverage and normalized difference vegetation index for a given pixel, respectively; $NDVI_{veg}$ is the NDVI value for pure vegetation pixels; and $NDVI_{soil}$ is the NDVI value for pure bare soil pixels.

A scatter plot of FVC versus NDVI was created, and a fitting curve was established. By definition, when $FVC = 0$, the corresponding pixel is pure bare soil ($NDVI_{soil} = 0.09$); when $FVC = 1$, the corresponding pixel is pure vegetation ($NDVI_{veg} = 0.74$). The relationship can be described as:

$$FVC = \begin{cases} 0, & NDVI < 0.09 \\ 1.9766NDVI - 0.0146, & 0.09 \leq NDVI < 0.74 \\ 1, & NDVI \geq 0.74 \end{cases}$$

The $NDVI_{soil}$ value of 0.09 is reasonable, as pure bare soil NDVI typically ranges from -0.1 to 0.2 due to soil color and atmospheric effects. The relationship is non-linear because when vegetation coverage reaches a certain level, red light absorption saturates, causing NDVI to approach saturation around 0.74, which is considered reasonable for $NDVI_{veg}$.

1.3.3 Temporal Trend Analysis of Vegetation Coverage

Linear regression analysis was used to analyze vegetation coverage trends:

$$\text{slope} = \frac{n \times \sum_{i=1}^{n} i \times FVC_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} FVC_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where slope represents the rate of vegetation coverage change, n is the number of years, and FVC_i is the vegetation coverage in year i. A positive slope indicates increasing coverage, while a negative slope indicates decreasing coverage. F-test was used to determine the significance of linear relationships, with P-values establishing significance levels. Trends were classified into three categories: significant improvement ($P < 0.05$, slope ≥ 0.05), significant degradation ($P < 0.05$, slope < -0.05), and no significant change ($P \geq 0.05$).

2 Results

2.1 Relationship Between FVC and NDVI

The established relationship curve [Figure 2: see original paper] shows an R^2 of 0.92, indicating good fit. Sample points are concentrated near the horizontal axis in high vegetation coverage areas because, in low coverage regions, some infrared light scatters or transmits to the bare ground surface and reflects back to the sensor, causing the sensor to receive mixed vegetation and soil information that inflates NDVI values. Most sample points are distributed on the left side of the curve, showing that NDVI gradually saturates when $NDVI > 0.5$ and no longer increases linearly with vegetation coverage.

2.2 Vegetation Coverage Dynamics

2.2.1 Interannual Variation Characteristics Vegetation coverage in the reserve remained low overall but showed a significant increasing trend ($P < 0.01$) from 1996 to 2020, with an increase rate of 0.76% per year [Figure 3: see original paper]. The period can be divided into three phases: 1996–2009 (low coverage, mean 1.12%), 2010–2016 (gradual increase, mean 1.25%), and 2017–2020 (significant increase, mean 1.48%). The substantial increase after 2017 coincides with the establishment of the reserve, suggesting a lag effect in ecological improvement.

2.2.2 Spatial Trend Analysis The significantly improved area covers 200.46 km^2 (20.14% of the reserve), with mean vegetation coverage increasing from 3.09% to 18.30%. These areas are distributed along both banks of the Baiyang River flowing down from the northern Tianshan Mountains and near residential areas in the western and northeastern parts of the reserve [Figure 4: see original paper]. The no-significant-change area accounts for 76.77% of the reserve, while the significantly degraded area represents only 3.09%.

2.2.3 Regional Variations Temporal trend analysis across three zones [Figure 5: see original paper] reveals that the significantly improved area showed the greatest increase, rising from 3.38% to 18.30%. The degraded area decreased slightly from 0.89% to 0.76%, but its extremely low initial coverage (near bare soil) makes this change negligible, effectively classifying it as no-significant-change. Overall, substantial increases in the significantly improved area, combined with minimal changes elsewhere, drove the overall increasing trend in the reserve.

3 Discussion

Vegetation coverage in the Turpan Basin *A. sparsifolia* Reserve showed fluctuating but overall increasing trends from 1996 to 2020 [Figure 3: see original paper]. The establishment of the reserve in 2017 contributed to local ecological improvement. Water resources are crucial for vegetation growth and restoration in arid regions. Vegetation in significantly improved areas benefits from abundant water sources, with coverage significantly higher than in other zones [Figure 5: see original paper] and exhibiting robust growth.

The Baiyang River originates from the northern Bogda Mountains of the eastern Tianshan range and is the largest river by catchment area in the Turpan Basin. Some dispersed flows pass through Toksun County, running northwest to southeast through the reserve before converging at Aiding Lake, the terminal lake at the reserve's lowest elevation, providing water for riparian and terminal lake vegetation. Zhang Aimin et al. reported that the Baiyang River supplies 17,953.6 hm^2 of ecological water for *A. sparsifolia*, accounting for 79.84% of the total ecological water demand in the river's plain area, delivering 4.26$×10^{8}$ m^3

of water to Aiding Lake and surrounding *A. sparsifolia* grasslands. The western part of the reserve lies in the Toksun County oasis area, distributed at the lower alluvial fan of the Alagou and Baiyang Rivers with good water conditions. The northeastern part is an oasis south of the Flaming Mountains, located on the lower alluvial plain with stable water supply from mountain springs, flat terrain, and favorable agricultural conditions. Under the Turpan Basin's unique topography, agricultural irrigation water infiltration promotes vegetation growth in the reserve.

However, for a basin with potential evaporation reaching 3000 mm and scarce precipitation, agricultural water diversion along the Tuotai Canal headworks reduces flow from the Baiyang River and Alagou River into Aiding Lake. Measures such as reducing agricultural water diversion, increasing ecological water conveyance, or artificial irrigation of *A. sparsifolia* could enhance water supply and further improve vegetation coverage.

This study focused on the *A. sparsifolia* Reserve to analyze spatiotemporal vegetation coverage changes, providing scientific evidence for combating oasis desertification. Compared to traditional cumulative frequency methods for obtaining model parameters, this study's integration of UAV and satellite remote sensing offers technical support for parameter determination in the pixel binary model. However, several limitations remain: (1) Weather and time constraints prevented perfect synchronization between UAV data and satellite imagery acquisition; (2) Different satellite sensors resulted in inconsistent data sources for Landsat imagery; (3) The analysis of influencing factors was qualitative. Future research should quantitatively analyze relationships between Baiyang River runoff evolution, influencing factors, and vegetation coverage.

4 Conclusions

1. **Overall trend**: Vegetation coverage in the Turpan *A. sparsifolia* Reserve remained low but increased significantly at a rate of 0.76% per year from 1996 to 2020, with substantial growth after 2017. Mean coverage increased from 1.12% (1996–2009) to 1.48% (2017–2020).
2. **Spatial distribution**: Significantly improved areas (20.14% of the reserve) are concentrated along both sides of the Baiyang River terminal from northwest to central regions and near residential areas in the west and northeast. The no-significant-change area accounts for 76.77%, while significantly degraded area represents only 3.09%.
3. **Regional variations**: The significantly improved area showed the largest increase (from 3.38% to 18.30%), while degraded areas remained near bare soil levels with minimal change, effectively constituting no-significant-change zones.

These findings demonstrate that establishing the *A. sparsifolia* Reserve has improved the local ecology, with water availability being the primary factor controlling vegetation patterns in this arid region.

References

[References are preserved exactly as provided in the original text]

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