Vegetation Cover Dynamics and Their Driving Factors in the Oasis-Desert Ecotone: A Case Study of Cele, Xinjiang (Postprint)

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Abstract

The oasis-desert ecotone is an ecological buffer zone between oasis and desert ecosystems, playing a crucial ecological role in maintaining oasis stability and preventing wind erosion. Taking the Cele Oasis-Desert Ecotone as an example, this study selected Landsat remote sensing imagery data, meteorological and socio-economic data from 1993 to 2017, and employed the Normalized Difference Vegetation Index (NDVI), pixel dichotomy model, and principal component analysis to investigate long-term vegetation dynamics and their driving factors in a small-scale region. The results show: (1) Over the past 25 years, the annual mean NDVI in the Cele Oasis-Desert Ecotone exhibited a year-by-year increasing trend, with high NDVI values mainly distributed in its southeastern part, while low NDVI values were primarily found in its western and northwestern regions; (2) The multi-year average fractional vegetation coverage (FVC) was 0.23, with the FVC values for the six periods of 1993, 1998, 2008, 2011, 2014, and 2017 being 0.20, 0.18, 0.19, 0.23, 0.27, and 0.28, respectively, indicating a continuous increase in vegetation coverage; (3) Vegetation coverage was predominantly characterized by medium and low coverage, accounting for 30.73% and 21.47% of the total study area, respectively, followed by low, relatively high, high, and very low coverage vegetation, which occupied 21.48%, 20.39%, 20.12%, and 7.26% of the total area, respectively. Areas with significantly improved vegetation coverage were relatively small and mainly concentrated in the central and southeastern parts and around the Cele River basin, while vegetation coverage of other change classes was more scattered; (4) At the interannual time scale, human activities were the dominant factor influencing vegetation changes in the Cele Oasis-Desert Ecotone, with vegetation showing greater sensitivity to precipitation and atmospheric relative humidity than to temperature. Specifically, artificial afforestation, cultivated land area, population size, and shelterbelt area loaded at 0.850, 0.810, 0.853, and 0.779 in the first principal component, respectively; atmospheric relative humidity, precipitation, and livestock inventory loaded at 0.845, 0.753, and -0.608 in the second principal component, respectively; and temperature loaded at 0.883 in the third principal component. This study provides a theoretical basis for further understanding vegetation dynamics, influencing factors, and vegetation conservation and restoration in oasis-desert ecotones.

Full Text

Dynamic Changes and Driving Factors of Vegetation Cover in the Oasis-Desert Ecotone: A Case Study of Cele, Xinjiang

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Abstract

The oasis-desert ecotone serves as an ecological buffer zone between oasis and desert ecosystems, playing a vital role in maintaining oasis stability and providing windbreak and sand fixation functions. Taking the Cele oasis-desert ecotone as an example, this study utilized Landsat remote sensing imagery data alongside meteorological and socioeconomic data to investigate long-term vegetation dynamics and their driving factors in a small-scale region using the Normalized Difference Vegetation Index (NDVI), pixel dichotomy model, and principal component analysis. The results indicate that: (1) the multi-year average vegetation coverage was 0.23, with vegetation coverage continuously increasing over time; (2) vegetation coverage was predominantly medium and low, accounting for 30.73% and 21.47% of the study area respectively, followed by low, higher, high, and very low coverage vegetation at 21.48%, 20.39%, 20.12%, and 7.26% respectively; (3) areas with significantly improved vegetation coverage were relatively small and concentrated primarily in the central and southeastern regions and around the Cele River basin, while other vegetation cover change classes were more dispersed; and (4) at the interannual timescale, human activities represent the dominant factor influencing vegetation change in the Cele oasis-desert ecotone, with vegetation showing greater sensitivity to precipitation and atmospheric relative humidity than to temperature. Specifically, artificial afforestation area, cultivated land area, population size, and shelterbelt area accounted for 0.850, 0.810, 0.853, and 0.779 respectively in the first principal component, while atmospheric relative humidity, precipitation, and livestock inventory accounted for 0.845, 0.753, and 0.608 in the second principal component, and temperature accounted for 0.883 in the third principal component. This study provides a theoretical basis for further understanding vegetation dynamics, influencing factors, and vegetation conservation and restoration in oasis-desert ecotones.

Keywords: Normalized Difference Vegetation Index; vegetation coverage; oasis-desert ecotone; influencing factors; principal component analysis

1. Introduction

Vegetation constitutes a crucial component of terrestrial ecosystems and plays a significant role in maintaining sustainable development of global and regional ecosystems. Vegetation coverage, as a key indicator for measuring surface vegetation conditions and describing ecosystem environments, serves as a sensitive indicator of ecological environmental changes and holds great significance for soil and water conservation, regional environmental quality assessment, and ecosystem evaluation. Previous studies have demonstrated that precipitation and temperature are two primary factors affecting regional vegetation cover change, and with intensifying human activities, vegetation cover change is increasingly recognized as the combined result of climate change and human activities.

Oases represent typical landscape features in the arid regions of northwestern China, where the stability and healthy development of their ecological environments are critical. The oasis-desert ecotone, composed of oasis and desert ecosystems, is highly sensitive to climate change and human activities, serving as an important natural ecological barrier for maintaining oasis ecological security and preventing wind erosion and sand fixation. Therefore, in-depth investigation of vegetation dynamics and driving factors in this special zone is of important theoretical and practical significance for ensuring the stability of oasis and desert ecosystems.

The Cele oasis-desert ecotone, located on the southern margin of the Taklimakan Desert, has become a hotspot for recent research. Under the dual influence of global warming and human activities, ecological environmental issues in northwestern China’ s arid regions have become increasingly prominent, with vegetation changes serving as a key entry point for studying regional ecological evolution and climate change responses. With the rapid development of remote sensing technology, using remote sensing data to study regional vegetation changes has become a major trend. However, most studies have focused on large- and medium-scale regions using short-term, low-resolution MODIS NDVI data, while research using higher-resolution Landsat imagery to analyze long-term vegetation changes and their driving factors in small-scale regions remains relatively rare.

This study takes the Cele oasis-desert ecotone in Xinjiang as an example, selecting the northwestern ecotone—most affected by wind-sand activities and intense human disturbance—as the research area. Using multi-year Landsat imagery data, we analyzed vegetation cover dynamics and driving factors in this region to understand recent vegetation changes and their influencing factors, providing a theoretical basis for further understanding vegetation dynamics, influencing factors, and vegetation conservation and restoration in oasis-desert ecotones.

2. Data Sources and Research Methods

2.1 Data Sources and Preprocessing

Landsat remote sensing imagery data were obtained from the Geospatial Data Cloud platform of the Chinese Academy of Sciences' Computer Network Information Center (http://www.gscloud.cn). Due to significant weather impacts on satellite imagery, we selected images with cloud cover below 10% during the vegetation growing season. Using ENVI 5.3 software, we performed spatial cropping, radiometric calibration, and atmospheric correction as standard preprocessing steps. Given that vegetation growth peaks during summer and autumn, and following previous research indicating that July-August remote sensing data best represents vegetation conditions in southern Xinjiang, we selected imagery from these months to calculate NDVI and vegetation coverage.

Specifically, we used Landsat 5-TM images for years up to 2011 and Landsat 8-OLI images for 2014 and 2017. Vegetation change is a gradual process; to clearly demonstrate dynamic changes in vegetation coverage, we performed visual expression and spatiotemporal change analysis on the imagery. Meteorological data (temperature, precipitation, and atmospheric relative humidity) and human activity data (population, cultivated land area, afforestation area, shelterbelt area, and annual livestock inventory) were all provided by the Cele National Station of Observation and Research for Desert Grassland Ecosystem in Xinjiang, Chinese Academy of Sciences.

2.2 NDVI Calculation and Vegetation Coverage Classification

The Normalized Difference Vegetation Index (NDVI), also known as the standardized vegetation index, offers high sensitivity, wide identification range, and effective elimination of terrain and community structure shadow and radiation interference, making it widely applicable in vegetation coverage research. The calculation formula is:

$$NDVI = (NIR - R)/(NIR + R)$$

where NIR represents the near-infrared band (band 4 in Landsat 5-TM, band 5 in Landsat 8-OLI) and R represents the red band (band 3 in Landsat 5-TM, band 4 in Landsat 8-OLI).

NDVI values range between [-1, +1], with positive values indicating vegetation coverage (higher values = greater coverage) and negative values representing water, snow, or bare rock. To classify vegetation coverage levels—an important indicator for assessing desert vegetation growth status—we used the pixel dichotomy model based on calculated NDVI values:

$$FVC = (NDVI - NDVI_{soil})/(NDVI_{veg} - NDVI_{soil})$$

where $NDVI_{soil}$ represents NDVI values for completely bare soil or non-vegetated pixels, and $NDVI_{veg}$ represents NDVI values for fully vegetated pixels. Due to uncertainty in these values under varying temporal, atmospheric, and surface moisture conditions, we adopted approximate values based on cumulative frequency statistics: $NDVI_{soil}$ at 0.5% cumulative frequency and $NDVI_{veg}$ at 99.5% cumulative frequency.

Using ArcGIS software, we reclassified the calculated vegetation coverage into five levels based on national desertification survey standards and previous research: very low coverage (<10%), low coverage (10-30%), medium coverage (30-60%), high coverage (60-80%), and higher coverage (>80%). To analyze vegetation cover change, we performed raster difference operations between consecutive periods ($D = FV_{t2} - FV_{t1}$) and between the final and initial periods to determine overall change trends, where negative values indicate degradation and positive values indicate improvement.

2.3 Principal Component Analysis

Based on previous research, we selected eight factors influencing vegetation dynamics: temperature (°C), precipitation (mm), atmospheric relative humidity (%), afforestation area (hm^2), cultivated land area (hm^2), population (people), shelterbelt area (hm^2), and livestock inventory (heads). Principal component analysis was employed to quantify the contribution rates of these factors to vegetation cover change in the Cele oasis-desert ecotone. The process involved: (1) standardizing raw data to eliminate scale effects; (2) calculating correlation coefficient matrices; (3) computing eigenvalues and eigenvectors; (4) determining principal components based on cumulative contribution rates exceeding 85%; and (5) analyzing factor loadings to identify primary influences.

3. Results

3.1 Spatiotemporal Characteristics of NDVI

Between 1993 and 2017, the overall NDVI of the Cele oasis-desert ecotone showed an increasing trend, with multi-year average values of 0.20, 0.18, 0.19, 0.23, 0.27, and 0.28 for the respective years. The spatial distribution pattern remained generally consistent, with high values concentrated in the southeast near the Cele oasis and low values in the west and northwest near the Taklimakan Desert margin. During 1993-1998, the high-value range expanded slightly but not significantly. From 1998-2008, vegetation coverage increased overall, though remaining predominantly low to medium. Changes between 2008-2011 were minimal, with only very low coverage areas showing some reduction. After 2011, the spatial distribution of high NDVI values expanded noticeably, particularly near the oasis edge where vegetation coverage increased significantly in blocks. After 2014, overall vegetation coverage improved markedly, with very low coverage areas gradually decreasing and vegetation cover exhibiting a spatial pattern of decreasing from the oasis center outward toward the desert.

3.2 Vegetation Coverage Characteristics

3.2.1 Overall Vegetation Coverage Features The multi-year average vegetation coverage of the Cele oasis-desert ecotone was 0.23. Medium coverage represented the largest area (30.73% of the study area), followed by low (21.48%), higher (20.39%), high (20.12%), and very low (7.26%) coverage. Between 1993-1998, low and medium coverage areas increased by 1.45 km^2 and 2.20 km^2 respectively, while very low and higher coverage areas decreased by 0.82 km^2 and 0.19 km^2. During 1998-2008, vegetation coverage showed an overall decreasing trend, with very low and low coverage areas increasing by 0.85 km^2 and 1.06 km^2 respectively, while medium and higher coverage areas decreased by 0.14 km^2 and 2.06 km^2. From 2008-2011, very low, higher, and high coverage areas increased by 0.10 km^2, 0.19 km^2, and 0.12 km^2 respectively, while low and medium coverage areas decreased by 1.65 km^2 and 0.19 km^2. During 2011-2014, low and medium coverage areas increased by 3.06 km^2 and 0.88 km^2, while very low and higher coverage areas decreased by 0.07 km^2 and 3.1 km^2, indicating overall vegetation improvement. In 2014-2017, very low coverage and higher coverage areas increased by 0.1 km^2 and 1.45 km^2 respectively, while low and medium coverage areas decreased by 2.06 km^2 and 0.19 km^2, with other classes showing minimal change.

3.2.2 Vegetation Coverage Change Classification Analyzing spatiotemporal change data from 1993-2017, we classified vegetation coverage changes into seven levels. The classification standards and area proportions show that "basically unchanged" dominated all periods, accounting for 60.73%, 59.70%, 68.61%, 62.27%, and 63.72% of the total area respectively. Areas of slight degradation and slight improvement showed minor differences, while areas of significant improvement and significant degradation were relatively small. Throughout the entire study period, the ranking of change levels by area was: basically unchanged > slight degradation > slight improvement > significant improvement > significant degradation, with average proportions of 62.27%, 19.73%, 15.00%, 2.87%, and 1.70% respectively.

Spatially, areas with significantly improved vegetation coverage were concentrated in the central, southeastern, and Cele River basin regions, distributed in patches, while other change classes were more dispersed. The vegetation cover change pattern indicates that while overall vegetation improved, fluctuations were substantial, with very low coverage areas being unstable, low coverage areas expanding, medium and higher coverage areas decreasing, and high coverage areas showing large fluctuations.

3.3 Analysis of Driving Factors

3.3.1 Trends in Climate Change and Human Activities Meteorological factors showed that mean annual temperature exhibited a fluctuating upward trend from 1993-2017, while precipitation and atmospheric relative humidity showed consistent patterns with large fluctuations. In terms of human activities, both population and cultivated land area increased significantly, with cultivated land area growing slowly before 2000 but increasing dramatically afterward, from 16,790 hm^2 to 25,500 hm^2, and continuing to grow slowly thereafter. Population showed an approximately linear growth trend, increasing by nearly 2×10^{4} people every five years. Artificial afforestation and shelterbelt areas increased sharply, particularly after 2000, while livestock inventory increased slowly with large fluctuations. These trends indicate that population growth drove cultivated land expansion, which in turn necessitated increased shelterbelt and afforestation areas to protect against wind erosion.

3.3.2 Factor Selection and Principal Component Analysis Principal component analysis of standardized data yielded a correlation matrix showing most inter-factor correlation coefficients exceeded 0.3, indicating suitability for PCA. We selected the first three principal components with cumulative variance contribution exceeding 85% to analyze factors influencing vegetation change. The first principal component (contribution rate: 52.38%) was heavily loaded with afforestation area (0.850), cultivated land area (0.810), population (0.853), and shelterbelt area (0.779). The second principal component (contribution rate: 21.77%) showed high loadings for atmospheric relative humidity (0.845), precipitation (0.753), and livestock inventory (0.608). The third principal component (contribution rate: 12.69%) was dominated by temperature (0.883).

These results demonstrate that human activities are the primary driver of vegetation change in the Cele oasis-desert ecotone, with climate factors being secondary. Vegetation shows greater sensitivity to precipitation and atmospheric relative humidity than to temperature, consistent with previous research findings. Although some studies suggest vegetation responds more to temperature than precipitation, analysis shows that while Cele' s mean temperature has risen, maximum temperatures haven' t changed significantly, whereas precipitation has increased with anomalous years. Temperature rise may provide needed heat for vegetation growth but also accelerates evaporation, making vegetation more sensitive to precipitation and humidity changes.

4. Discussion

Throughout the 1993-2017 study period, vegetation coverage in the oasis-desert ecotone showed an overall increasing trend, though with banded reduction patterns. The spatial distribution exhibited a decreasing gradient from the oasis center outward to the desert, with the ecotone gradually shifting toward the desert and narrowing in width. This aligns with previous research showing vegetation cover and species diversity generally increase from the desert front toward the oasis, though with scattered local distributions. The primary cause is farmland reclamation at the oasis edge, reducing natural vegetation. The northwestern ecotone of Cele lies downwind of prevailing westerly and northwesterly winds, where severe wind-sand hazards damage vegetation through sand cutting and burial, with damage decreasing from desert to oasis. Additionally, population growth, cultivated land expansion, and shelterbelt construction have significantly increased vegetation coverage within the oasis and extended it toward the desert, though patchy distributions in the ecotone likely result from local topography and soil nutrients.

The region's extremely arid climate and abundant sand sources create harsh conditions for vegetation growth, with even lower coverage in the desert-adjacent ecotone. While interannual variations in precipitation, temperature, and vegetation coverage are relatively small, intra-annual changes are more pronounced. At interannual timescales, human activities thus have more significant impacts on vegetation cover than climate factors. Livestock inventory indirectly reflects grazing impacts, showing a negative correlation with vegetation coverage, though its relatively small loading in PCA suggests limited influence, likely due to grazing prohibition and firewood collection bans implemented in recent years. Additionally, improved canal lining rates with oasis expansion have reduced groundwater seepage, causing decline in some desert vegetation dependent on groundwater.

Government policies have also played important regulatory roles. Early rapid population growth and irrational water resource use, deforestation, and overcutting caused severe vegetation degradation and wind-sand invasion. However, increased attention to wind-sand control, the "Three-North"Shelterbelt Program, sand enclosure for vegetation restoration, and other measures have significantly improved the ecological environment and increased vegetation coverage since the mid-1990s, particularly through afforestation and sand control efforts in the northwestern ecotone since 2000. Besides climate and human activities, factors such as groundwater, topography, soil moisture, temperature, and nutrients directly affect vegetation changes and should be incorporated in future research using multiple data sources and quantitative analysis methods.

5. Conclusions

This study analyzed the Cele oasis-desert ecotone using 1993-2017 Landsat imagery and meteorological and socioeconomic data, employing NDVI, pixel dichotomy model, and principal component analysis to investigate long-term vegetation dynamics and driving factors. The main conclusions are:

1) Vegetation coverage in the Cele oasis-desert ecotone showed large spatiotemporal fluctuations but an overall increasing trend, expanding gradually from southeast to northwest. Temporally, vegetation coverage increased yearly, with multi-year average NDVI of 0.23. Spatially, high NDVI values were concentrated in the southeast near the oasis, while low values occurred in the west and northwest adjacent to the Taklimakan Desert, forming an expansion pattern from the oasis center outward through the ecotone.

2) During 1993-2017, low and medium vegetation coverage dominated, with very low coverage showing significant change. Low coverage areas expanded, medium and higher coverage areas decreased, and high coverage areas fluctuated substantially. Medium coverage represented the largest proportion (30.73%), followed by low (21.48%), higher (20.39%), high (20.12%), and very low (7.26%) coverage. Vegetation change was predominantly classified as "basically unchanged," accounting for 60.73-68.61% of the area across periods, with slight degradation and improvement showing minor differences, and significant changes occupying small areas.

3) Human activities constitute the dominant factor influencing vegetation change, followed by climate factors. Artificial afforestation area, cultivated land area, population, and shelterbelt area had large loadings in the first principal component (0.850, 0.810, 0.853, and 0.779 respectively), while atmospheric relative humidity, precipitation, and livestock inventory dominated the second principal component (0.845, 0.753, and 0.608 respectively). Temperature was the main factor in the third principal component (0.883). Vegetation sensitivity to precipitation and atmospheric relative humidity exceeded that to temperature.

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