Spatiotemporal Dynamics of Grassland in Xinjiang and Its Response to Climate Change: A Case Study of Changji Hui Autonomous Prefecture (Postprint)

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Abstract

Based on MODIS NPP and EVI remote sensing imagery, using the MVC method, simple linear regression, and Pearson correlation analysis, this study investigates the spatiotemporal dynamics of grassland vegetation in Changji Prefecture on the northern slope of the Tianshan Mountains and its response to concurrent temperature and precipitation. The results show: from 2000 to 2020, grassland vegetation NPP and EVI both exhibited stepwise significant increases, followed by a year-by-year decreasing trend after 2016; the multi-year averages of NPP and EVI were 0.095 kg C·m-2 and 0.186, respectively; compared with 2000 (NPP=0.077 kg C·m-2, EVI=0.166), NPP (0.099 kg C·m-2) and EVI (0.194) in 2020 increased by 28.57% and 16.87%, respectively. The spatial heterogeneity of grassland NPP increased significantly and showed an expanding trend, while the spatial variation of EVI increased year by year, with ranges of variation of 0.038 kg C·m-2 (NPP) and 0.059 (EVI), respectively. Spatially, the multi-year average distributions of NPP and EVI differed; overall, NPP and EVI increased with altitude, but high EVI values were distributed at oasis margins and the southern margin of the Gurbantunggut Desert, with NPP and EVI showing significant increases in areas accounting for 65.01% and 21.93% of the total area, respectively. For the nine grassland types, the area proportion of vegetation NPP and EVI showing significantly positive correlations with precipitation was much greater than that with concurrent temperature, and different grassland types exhibited varying responses to precipitation. Precipitation is an important influencing factor for grassland vegetation, but moderate warming in high-altitude regions is beneficial to grassland vegetation growth.

Full Text

Abstract

Based on MODIS NPP remote sensing imagery, this study employs maximum value composition, linear regression, and Pearson correlation analysis to investigate the spatiotemporal dynamics of grassland vegetation on the northern slope of the Tianshan Mountains in Changji Hui Autonomous Prefecture and its response to concurrent temperature and precipitation variations. The results demonstrate that grassland vegetation NPP and EVI exhibited a significant increasing trend from 2000 to 2020 ($P < 0.05$), with pronounced interannual fluctuations. However, both NPP and EVI began declining year by year after 2016. The multi-year mean values were 0.095 kg $C \cdot m^{-2}$ for NPP and 0.186 for EVI. By 2020, NPP (0.099 kg $C \cdot m^{-2}$) and EVI (0.194) had increased by 28.57% and 16.87%, respectively, compared to 2000 (NPP = 0.077 kg $C \cdot m^{-2}$; EVI = 0.166). Spatial heterogeneity increased significantly year by year, with variation ranges of 0.038 kg $C \cdot m^{-2}$ for NPP and 0.059 for EVI. Spatially, the distributions of NPP and EVI showed differences but generally increased with altitude. However, high-value areas were distributed along oasis edges and the southern margin of the Gurbantunggut Desert. The area proportions showing significant positive correlations with precipitation were substantially greater than those with temperature for all grassland types, though responses to precipitation varied among types. Precipitation represents a critical factor influencing grassland vegetation, while moderate warming at high altitudes benefits grassland growth.

Keywords: grassland; ephemeral plants; warm-humidification; MODIS NPP; MODIS EVI; spatiotemporal dynamics; northern slope of the Tianshan Mountains

Introduction

Grassland ecosystems cover more than 40% of the Earth' s terrestrial surface, representing the most widely distributed ecosystem type and serving as a crucial terrestrial ecological barrier in China. Grasslands function as important livestock production bases and carriers of grassland culture, while providing production, regulation, support, and cultural services that maintain ecological security, sustainable development, and human well-being. The Xinjiang Tianshan Mountains North Slope Economic Belt, located north of the Tianshan Mountains and south of the Junggar Basin, constitutes a core region of the "Belt and Road" initiative. Over the past half-century, climate change and large-scale water-soil development have intensified land desertification (degradation, sandification, and salinization) on the northern Tianshan slope, with grassland degradation becoming particularly severe.

In recent years, integrated "space-ground" monitoring has been gradually applied to grassland ecology, prompting numerous domestic scholars to conduct research on the northern Tianshan slope. Studies have quantified grassland biomass, vegetation coverage, and net primary productivity using aerospace remote sensing technologies. Other researchers have investigated the impacts of grazing activities on grassland ecosystem biomass, soil organic carbon, and microbial activity on the northern Tianshan slope. Additional work has analyzed the effects of short-term grazing exclusion and enclosure on community characteristics, carbon storage, and carbon-nitrogen exchange in these grassland ecosystems. While existing research has explored degradation characteristics, causes, and soil-microorganism relationships, studies specifically focusing on Changji Hui Autonomous Prefecture (hereafter "Changji Prefecture") remain limited, particularly regarding long-term spatiotemporal grassland changes. Changji Prefecture, located in the central-eastern section of the northern Tianshan slope, exhibits vertical zonation in grassland distribution and serves as a typical region for studying northern Tianshan grasslands with important demonstration and promotion value.

1. Materials and Methods

1.1 Study Area

Changji Hui Autonomous Prefecture is situated on the northern foothills of the Tianshan Mountains and the southeastern edge of the Junggar Basin (43°20 ~45°00 N, 85°17 ~91°32 E), representing a key component of the "Silk Road" Economic Belt core zone. The terrain slopes from southeast to northwest, comprising mountains, alluvial plains, and basins from south to north. The climate is temperate continental, characterized by cold winters, hot summers, large diurnal temperature ranges, and intense evapotranspiration. The multi-year average temperature is 6.8°C, with maximum and minimum temperatures of 24.5°C and -15.6°C, respectively. Precipitation is higher in summer than winter, with a multi-year average of 190 mm. The usable natural grassland area is approximately 5.20×10^{6} hm^2 (accounting for 65.01% of the prefecture' s total area). Grassland types include alpine steppe, alpine meadow, mountain meadow, temperate meadow steppe, temperate steppe, temperate desert steppe, temperate steppe-desert, temperate desert, and lowland meadow.

1.2 Data Sources and Preprocessing

This study utilized MODIS satellite imagery, natural grassland classification data, and Xinjiang administrative boundaries. Net Primary Productivity (NPP), Enhanced Vegetation Index (EVI), and related datasets spanning 2000-2020 were obtained at 0.5 km spatial resolution and annual temporal resolution. MODIS data were downloaded from https://ladsweb.modaps.eosdis.nasa.gov/search/. Natural grassland classification data were provided by the Xinjiang Uygur Autonomous Region Grassland Station. Temperature and precipitation data (2000-2020) were obtained from the Resource and Environment Science and Data Center (https://www.resdc.cn/). Data preprocessing, analysis, and visualization were conducted using Python programming language with Arcpy, Numpy, and Matplotlib packages.

1.3 Methods

1.3.1 Maximum Value Composition and Descriptive Statistics At the grid scale, the maximum value composition method was applied to calculate annual grassland NPP and EVI (2000-2020), representing optimal annual growth conditions. The cumulative method calculated annual grassland NPP and EVI, representing total annual organic matter accumulation. At the prefecture and grassland type scales, annual NPP and EVI values were statistically analyzed, with standard deviations computed to characterize spatial heterogeneity variations and scale differences.

1.3.2 Temporal Trend Analysis of Grassland Vegetation Pixel-based interannual change rates characterized grassland vegetation trends through linear regression. The slope was calculated as:

$$Slope = \frac{n \times \sum_{i=1}^{n}(i \times EVI_i) - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} EVI_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where n represents the time span (n = 21) and i denotes the study year sequence. The slope indicates the trend magnitude and direction, with t-tests performed for significance testing. Positive slopes indicate increasing trends, negative slopes indicate decreasing trends, and values near zero suggest no significant change.

1.3.3 Correlation Analysis Pearson correlation analysis quantified relationships between grassland NPP/EVI and concurrent climate factors (temperature, precipitation):

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where r_{xy} is the correlation coefficient between variables x and y, ranging from -1 to 1. Positive values indicate positive correlation, negative values indicate negative correlation, and the absolute value represents correlation strength.

2. Results

2.1 Spatiotemporal Dynamics of Grassland Vegetation

2.1.1 Temporal Variations From 2000 to 2020, Changji Prefecture grassland NPP and EVI showed significant increasing trends ($P < 0.05$) with notable interannual fluctuations. However, both indices began decreasing annually after 2016, marking an important inflection point. The multi-year mean NPP was 0.095 kg $C \cdot m^{-2}$, with minimum and maximum values of 0.073 kg $C \cdot m^{-2}$ (2000) and 0.138 kg $C \cdot m^{-2}$ (2016), respectively. Interannual fluctuations expanded gradually, with NPP maintaining high-level oscillations before 2016 and showing sharp reductions thereafter. EVI exhibited similar patterns, with a multi-year mean of 0.186 and variation range of 0.059.

Spatial heterogeneity (standard deviation) increased significantly for both NPP and EVI. The variation range for NPP was 0.038 kg $C \cdot m^{-2}$, with mean spatial differences of 0.099 kg $C \cdot m^{-2}$. The highest spatial heterogeneity occurred in 2016, with substantial interannual variation. Overall, spatial differences increased annually, with 65.01% of grassland area showing significant increasing trends (Slope > 0, $P < 0.05$) and 21.93% showing significant decreasing trends (Slope < 0, $P < 0.05$).

2.1.2 Spatial Distribution Patterns and Interannual Trends The spatial distribution of grassland NPP and EVI differed but generally increased with altitude. High-value areas (NPP > 0.30 kg $C \cdot m^{-2}$) were concentrated in mountainous regions, while low-value areas (NPP < 0.15 kg $C \cdot m^{-2}$) occupied the northern Tianshan piedmont and southern Gurbantunggut Desert margin. Areas with NPP < 0.05 kg $C \cdot m^{-2}$ covered the largest proportion (37.37%) but showed the lowest standard deviation (0.03 kg $C \cdot m^{-2}$), indicating relatively uniform low productivity.

Pixel-based significance testing revealed that 65.01% of grassland area showed significant increasing trends, while 21.93% showed significant decreasing trends. Grassland with NPP > 0.15 kg $C \cdot m^{-2}$ accounted for 20.45% of total grassland area, primarily distributed in mountainous regions and representing key areas for grazing prohibition and balance implementation. EVI patterns were similar, with 62.83% of area showing EVI < 0.15 and 37.17% showing EVI > 0.15.

2.2 Temporal Changes by Grassland Type

Analysis of nine grassland types as sub-regions revealed that all types except alpine steppe showed significant increasing trends ($P < 0.05$). Lowland meadow, alpine meadow, temperate steppe-desert, and temperate desert types exhibited fluctuating increases, while temperate meadow steppe and temperate steppe showed strong interannual oscillations. Mountain meadow and temperate desert steppe types demonstrated significant increasing trends with annual fluctuations.

The coefficient of determination (R^2) varied among types, indicating different interannual oscillation patterns. Lowland meadow, alpine meadow, alpine steppe, mountain meadow, and temperate steppe showed $R^2 > 0.50$, while temperate meadow steppe, temperate steppe-desert, and temperate desert had $R^2 < 0.50$, suggesting weaker temporal fitting.

2.3 Relationships Between Grassland Dynamics and Climate

2.3.1 Spatiotemporal Climate Patterns Mean annual temperature in Changji Prefecture ranged from -7.91°C to 8.94°C, with a multi-year average of 6.09°C. Mean annual precipitation was 147.71 mm, ranging from 78.90 mm to 678.90 mm. Temperature was higher in plains than mountains, while precipitation showed the opposite pattern. Warming areas were concentrated in central and southern Changji City, Hutubi County, and Manas County, as well as northern Qitai County and central Mulei County. Precipitation increases were mainly in the southeastern study area.

2.3.2 Correlations Between Grassland Vegetation and Climate Correlation analysis revealed that 43.05% of grassland area showed positive correlations with precipitation, significantly higher than the 17.65% showing positive correlations with temperature. Areas with significant positive correlations with precipitation ($r_{xy} > 0$, $P < 0.05$) accounted for 39.35%, compared to only 1.38% with temperature. Negative correlations occupied 27.63% for precipitation and 3.53% for temperature. Overall, grassland vegetation responded more strongly to precipitation than temperature.

2.3.3 Responses of Different Grassland Types All grassland types except alpine steppe showed significant positive correlations with precipitation ($r_{xy} > 0$, $P < 0.05$). Lowland meadow, alpine steppe, mountain meadow, and temperate steppe had greater proportions of area showing significant positive correlations with precipitation than with temperature. Lowland meadow and temperate desert steppe showed particularly strong precipitation responses, with 62.62% and 75.81% of area exhibiting significant positive correlations, respectively. High-altitude grasslands (mountain meadow, alpine meadow) also demonstrated strong precipitation responses, while low-altitude grasslands showed even more pronounced sensitivity to precipitation variations.

3. Discussion

Under climate change, the northern Tianshan slope exhibits "warm-humidification" trends, with Changji Prefecture' s warming and moistening climate favoring grassland vegetation growth. Grassland NPP and EVI generally increase with altitude, showing vertical zonation consistent with the region' s hydrothermal distribution pattern. Terrain significantly influences grassland distribution, with different topographic positions developing distinct hydrothermal combinations that support various grassland types.

The substantial increase in spatial heterogeneity of Changji Prefecture grassland vegetation ($P < 0.05$) reflects strong interannual oscillations. Despite overall climate warming and moistening, different grassland types respond differently to temperature and precipitation changes. The inflection point around 2016 suggests complex interactions between climate factors and vegetation dynamics.

Precipitation remains the primary limiting factor for grassland vegetation in this arid region, though moderate warming at high altitudes benefits growth. The formation of vigorous ephemeral plant layers during favorable hydrothermal conditions (April-June) contributes to high EVI values along oasis edges and desert margins. These short-lived plants, with their rapid development and high photosynthetic efficiency, complete their life cycles before the hot-dry season, significantly influencing seasonal vegetation indices.

4. Conclusion

This study analyzed MODIS NPP imagery and climate data to quantify spatiotemporal dynamics of natural grassland and its response to climate change in Changji Prefecture from 2000 to 2020. Key findings include:

1. Grassland NPP and EVI showed significant increasing trends ($P < 0.05$) from 2000-2020, with 2016 serving as an important inflection point after which both indices declined. Spatial heterogeneity increased significantly, with interannual fluctuations expanding over time.
2. Grassland NPP and EVI increased with altitude, showing vertical distribution patterns. Approximately 65.01% of grassland area exhibited significant increasing trends, while 30.01% showed decreasing trends. Topography and landforms are important factors influencing grassland distribution, with different hydrothermal conditions supporting diverse grassland types.
3. The proportion of grassland area showing significant positive correlations with precipitation was substantially greater than with temperature. All grassland types except alpine steppe showed stronger responses to precipitation than temperature, though responses varied among types. While precipitation remains the dominant factor, moderate warming at high altitudes benefits grassland vegetation growth.

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References

[1] Li F, Li B, Yan H, et al. Advances and prospects of grassland remote sensing research[J]. Chinese Journal of Grassland, 2022, 44(12): 87-99.

[2] Tuerxun Aishan, Tureniguli Amuti, Maimaiti Shawuti, et al. Grassland vitality monitoring based on remote sensing in Manas River Basin in northern slope of Tianshan mountain[J]. Bulletin of Soil and Water Conservation, 2016, 36(5): 140-145.

[3] Wang Y Q, Du B J, Zhang S Z, et al. Effects of grazing on soil aggregates and soil respiration potential in Tianshan mountain grassland, Xinjiang[J]. Acta Agrestia Sinica, 2022, 30(10): 2729-2736.

[4] Hu Y X, Gong J R, Zhu C C, et al. Spatial distribution of ecosystem services in the desert steppe, Inner Mongolia based on ecosystem service bundles[J]. Acta Prataculturae Sinica, 2023, 32(4): 1-14.

[5] Sun Z B, Gao M H, Cui X F, et al. Land use change in north slope economic zone of Tianshan mountain based on remote sensing and GIS from 2000-2015[J]. Journal of Beijing Normal University (Natural Science), 2018, 54(3): 397-404.

[6] Chen C B, Li G Y. Temporal and spatial variation of grassland NDVI in Kunlun Mountains, Altun Mountains and its responses to temperature and precipitation from 1981 through 2020[J]. Chinese Journal of Grassland, 2023, 45(2): 13-25.

[7] Zhao W K, Jing C Q, Chen C. Temporal and spatial variation of Xinjiang natural grassland and its responses to climate factors[J/OL]. Journal of Agricultural Science and Technology, 2022-11-21. doi: 10.13304/j.nykjdb.2021.0931.

[8] Du M J, Zheng J H, Ren X, et al. Effects of topography on the distribution pattern of net primary productivity of grassland in Changji Prefecture, Xinjiang[J]. Acta Ecological Sinica, 2018, 38(13): 4789-4799.

[9] Chen C, Jing C Q, Zhao W K, et al. Grassland quality response to climate change in Xinjiang and predicted future trends[J]. Acta Prataculturae Sinica, 2022, 31(12): 1-16.

[10] Tang H P, Yuan S F. Ephemeral Plants in Xinjiang, China[M]. Beijing: Higher Education Press, 2021.

[11] Chen C B, Peng J, Li G Y. Evaluating ecosystem health in the grasslands of Xinjiang[J]. Arid Zone Research, 2022, 39(1): 270-281.

[12] Li G Y, Chen C B, Li J L, et al. Advances in applying low altitude unmanned aerial vehicle remote sensing in grassland ecological monitoring[J]. Acta Ecological Sinica, 2023, 43(16): 1-13.

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