

Spatiotemporal Analysis of Natural Grassland NPP in Xinjiang over the Past 20 Years: Post-print

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Abstract

Based on MOD17A3HGF NPP (Net Primary Productivity) data along with temperature, precipitation, and other datasets, this study employed trend analysis and partial correlation analysis to investigate the spatiotemporal dynamics of natural grassland NPP in Xinjiang from 2000 to 2018 and its response to climate change at multiple scales (entire Xinjiang region, Northern Xinjiang and Southern Xinjiang, various prefectures/autonomous prefectures/cities, and 11 grassland types). The results indicate that: over the past 20 years, grassland NPP in Xinjiang exhibited a fluctuating increase, with a multi-year average of $0.103 \text{ kg C} \cdot \text{m}^{-2}$, gradually decreasing from the western Junggar Mountains, Ili River Valley, Tianshan Mountains, and Altai Mountains towards the Junggar Basin and Tarim Basin; the multi-year average NPP of grasslands in Northern Xinjiang ($0.149 \text{ kg C} \cdot \text{m}^{-2}$) was higher than that in Southern Xinjiang ($0.055 \text{ kg C} \cdot \text{m}^{-2}$), with both regions showing increasing trends; grassland NPP in various prefectures, autonomous prefectures, and cities showed an overall increasing trend, but with significant interannual variation; NPP of 11 natural grassland types (except the alpine desert type) displayed an increasing trend, though differences existed among different grassland types. After 2000, the warming and wetting climate in Xinjiang was conducive to grassland vegetation growth, but the enhanced interannual variation of precipitation led to dramatic interannual fluctuations in grassland NPP. The research results provide fundamental data for carbon budget assessment of natural grasslands in Xinjiang and can promote health evaluation and sustainable utilization of natural grasslands.

Full Text

Spatiotemporal Analysis of Natural Grassland NPP in Xinjiang in the Past 20 Years

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Abstract

Using MOD17A3HGF NPP data along with temperature and precipitation records, this study employs trend analysis and partial correlation analysis at multiple scales—including the entire Xinjiang region, northern and southern Xinjiang, various prefectures, and different grassland types—to investigate the spatiotemporal dynamics of natural grassland net primary productivity (NPP) and its response to climate change from 2000 to 2018. The results demonstrate that natural grassland NPP exhibited a fluctuating increasing trend over the study period, with a multi-year average of $0.103 \text{ kg C} \cdot \text{m}^{-2}$. Spatially, NPP gradually decreased from the western Junggar Mountains, Ili River Valley, Tianshan Mountains, and Altai Mountains toward the Junggar and Tarim Basins. The mean NPP in northern Xinjiang ($0.149 \text{ kg C} \cdot \text{m}^{-2}$) significantly exceeded that in southern Xinjiang ($0.055 \text{ kg C} \cdot \text{m}^{-2}$), though both regions showed increasing trends. Grassland NPP across all prefectures generally increased, but with distinct interannual variations. Among the eleven grassland types analyzed (excluding alpine desert), NPP showed increasing trends, though with notable differences between types. The warming-wetting trend in Xinjiang since 2000 has generally benefited grassland vegetation growth, but enhanced interannual precipitation variability has intensified fluctuations in grassland NPP. These findings provide fundamental data for assessing grassland carbon budgets and promote sustainable grassland management in Xinjiang.

Keywords: asymmetric warming-wetting; net primary productivity; spatiotemporal dynamics; space-earth observation; natural grassland in Xinjiang

1. Introduction

1.1 Study Area Overview

The Xinjiang Uygur Autonomous Region (hereafter “Xinjiang”) is located in northwestern China ($34^{\circ}22' - 49^{\circ}33' \text{ N}$, $73^{\circ}32' - 96^{\circ}21' \text{ E}$), covering an area of

1.66×10^6 km², approximately one-sixth of China's total land area. Characterized by a typical arid climate with strong continental influences, Xinjiang experiences low precipitation (annual average ~150 mm), high evaporation, and mean annual temperatures of 9–12°C. The region's topography follows a “three mountains surrounding two basins” pattern, with the Altai Mountains, Junggar Basin, Tianshan Mountains, Tarim Basin, and Kunlun Mountains arranged from north to south. Elevation ranges from -155 m (Ayding Lake in Turpan) to 8611 m (K2 peak). Based on geographic and climatic characteristics, Xinjiang is divided into northern and southern regions. Northern Xinjiang includes Urumqi, Wujiaqu, Shihezi, Karamay, Beitun, Shuanghe, Changji Hui Autonomous Prefecture, Bortala Mongol Autonomous Prefecture, and Ili Kazakh Autonomous Prefecture (including Altay and Tacheng). Southern Xinjiang comprises Aksu, Kashgar, Hotan, Kizilsu Kirghiz Autonomous Prefecture, Bayingolin Mongol Autonomous Prefecture, Turpan, Hami, Aral, Tumshuq, Tiemenguan, and Kunyu.

Xinjiang's unique natural environment, far from oceans and surrounded by mountains with enclosed basins, creates distinct spatial patterns of water and heat resources that support diverse natural grassland ecosystems. The region's grasslands cover $5,725.88 \times 10^4$ hm², ranking among China's five major pastoral areas. According to the Xinjiang grassland classification system, there are 11 major grassland types: alpine desert, alpine steppe, alpine meadow, mountain meadow, temperate meadow steppe, temperate steppe, temperate desert steppe, temperate steppe desert, temperate desert, lowland meadow, and swamp.

1.2 Data Sources and Preprocessing

The primary datasets included MOD17A3HGF NPP data, climate reanalysis data, and auxiliary information. The MOD17A3HGF Version 6 product (annual scale, 500 m spatial resolution) was obtained from NASA's LP DAAC. Grassland type classification data were provided by the Xinjiang Grassland Technical Promotion Station. Climate data (temperature and precipitation) were acquired from the China Meteorological Forcing Dataset, available through the National Tibetan Plateau Data Center. This dataset, based on GEWEX-SRB and Princeton GLDAS with fusion of China Meteorological Administration observations, offers superior accuracy compared to other reanalysis products.

Data preprocessing involved: (1) converting MOD17A3HGF data from HDF to GeoTIFF format, (2) mosaicking and projecting images, and (3) clipping to Xinjiang's administrative boundaries using ArcGIS 10.2. Climate data processing included converting precipitation rates to annual totals and calculating mean annual temperatures. All spatial operations employed the Geospatial Data Abstraction Library (GDAL) implemented in Python.

1.3 Research Methods

1.3.1 Statistical Analysis of Grassland NPP Using the MOD17A3HGF NPP dataset, we calculated annual statistics (mean, maximum, minimum, and standard deviation) at multiple scales: prefecture-level, northern/southern Xinjiang, and entire region. The multi-year average spatial pattern was derived from 2000–2018 NPP data. Grassland-type-specific NPP values were extracted by masking the NPP data with each grassland type classification. All spatial data processing, statistical calculations, and output operations were automated using GDAL in Python.

1.3.2 Interannual Variation Analysis Interannual variation rates were quantified using linear regression (least squares method) for each pixel:

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

where n is the study period length (19 years), i is the year index (1–19), and NPP is the NPP value in year i . The slope k represents the annual change rate: positive values indicate increasing trends, negative values indicate decreasing trends.

1.3.3 Correlation Analysis with Climate Factors Partial correlation analysis was conducted at the pixel scale to quantify relationships between NPP and climate variables (temperature, precipitation) while controlling for the other variable:

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

where r is the correlation coefficient between parameter x (NPP) and parameter y (temperature or precipitation), x and y are annual values, and $\bar{x}$ and $\bar{y}$ are multi-year means.

2. Results

2.1 Spatiotemporal Patterns of Natural Grassland NPP

2.1.1 Interannual Variation From 2000 to 2018, Xinjiang's natural grassland NPP showed a fluctuating increasing trend, with a multi-year average of $0.103 \text{ kg C} \cdot \text{m}^{-2}$. The 2018 value ($0.122 \text{ kg C} \cdot \text{m}^{-2}$) represented a 34.1% increase from 2000 ($0.091 \text{ kg C} \cdot \text{m}^{-2}$). The study period exhibited significant interannual variability, with alternating positive and negative growth years. The

maximum annual increment occurred in 2010 ($0.031 \text{ kg C} \cdot \text{m}^{-2}$), while the minimum occurred in 2004 ($-0.014 \text{ kg C} \cdot \text{m}^{-2}$). After 2010, interannual fluctuations intensified, with the standard deviation increasing from $0.014 \text{ kg C} \cdot \text{m}^{-2}$ (2000–2009) to $0.022 \text{ kg C} \cdot \text{m}^{-2}$ (2010–2018).

2.1.2 Spatial Distribution Pattern The multi-year average NPP displayed substantial spatial heterogeneity (Figure 4). High-value areas ($>0.50 \text{ kg C} \cdot \text{m}^{-2}$) were concentrated in the Ili River Valley, Tianshan Mountains, and Altai Mountains, while low-value areas ($<0.05 \text{ kg C} \cdot \text{m}^{-2}$) occupied the central Junggar Basin and Tarim Basin margins. Regions with NPP $>0.20 \text{ kg C} \cdot \text{m}^{-2}$ accounted for only 19.5% of total grassland area, primarily in the Ili River Valley, Altai Mountains, and Tianshan ranges. Conversely, 45.6% of grassland area had NPP $<0.05 \text{ kg C} \cdot \text{m}^{-2}$, distributed in the central Junggar Basin, northern Tianshan slopes, and Tarim Basin periphery. Approximately 80.5% of grassland area exhibited NPP below $0.20 \text{ kg C} \cdot \text{m}^{-2}$, indicating generally low productivity across Xinjiang.

The spatial pattern of interannual change rates (Figure 5) revealed that 63.1% of grassland area showed increasing trends, particularly in the Ili River Valley where increments exceeded $0.40 \text{ kg C} \cdot \text{m}^{-2}$. Decreasing trends were observed in 36.9% of area, mainly in the central Junggar Basin and eastern Tianshan regions.

2.2 Regional Variations in Grassland NPP

2.2.1 Northern vs. Southern Xinjiang Both northern and southern Xinjiang exhibited increasing NPP trends, but with notable differences. Northern Xinjiang's multi-year average NPP ($0.149 \text{ kg C} \cdot \text{m}^{-2}$) was substantially higher than southern Xinjiang's ($0.055 \text{ kg C} \cdot \text{m}^{-2}$), though northern Xinjiang showed greater interannual variability. The Ili Kazakh Autonomous Prefecture achieved the highest NPP ($0.365 \text{ kg C} \cdot \text{m}^{-2}$), followed by Bortala Mongol Autonomous Prefecture ($0.182 \text{ kg C} \cdot \text{m}^{-2}$) and Tacheng ($0.166 \text{ kg C} \cdot \text{m}^{-2}$). In southern Xinjiang, NPP ranged from 0.03 – $0.09 \text{ kg C} \cdot \text{m}^{-2}$ across prefectures, with Turpan showing the lowest values.

2.2.2 Prefecture-Level Variations All prefectures displayed increasing NPP trends, but with distinct interannual patterns (Figure 7). Northern prefectures (except Karamay) consistently outperformed southern prefectures. NPP values ranged from $0.037 \text{ kg C} \cdot \text{m}^{-2}$ (Hotan) to $0.30 \text{ kg C} \cdot \text{m}^{-2}$ (Ili), with most southern prefectures clustering below $0.09 \text{ kg C} \cdot \text{m}^{-2}$.

2.3 Grassland Type-Specific NPP Trends

Analysis of 11 grassland types revealed increasing trends for all categories except alpine desert (Figure 8). Mountain meadow showed the highest multi-year average NPP ($0.385 \text{ kg C} \cdot \text{m}^{-2}$), followed by swamp ($0.322 \text{ kg C} \cdot \text{m}^{-2}$) and

temperate meadow steppe ($0.223 \text{ kg C} \cdot \text{m}^{-2}$). Alpine desert exhibited minimal change ($0.002 \text{ kg C} \cdot \text{m}^{-2}$). Temperate desert steppe and temperate desert showed moderate values ($0.041\text{--}0.042 \text{ kg C} \cdot \text{m}^{-2}$), while temperate steppe desert displayed slight increases.

2.4 Response of Grassland NPP to Climate Factors

Spatial correlation analysis (Figure 9) revealed complex relationships between NPP and climate variables. NPP-temperature correlations were mixed: 41.74% of area showed positive correlation (primarily on northern Tianshan slopes in Changji and Urumqi), while 58.26% showed negative correlation, especially in southern Xinjiang. The mean correlation coefficient was -0.076. In contrast, NPP-precipitation correlations were predominantly positive (79.59% of area), with 20.41% showing high positive correlation concentrated in the Ili River Valley, northern Tianshan slopes, and western Junggar Mountains. The mean precipitation correlation coefficient was 0.076.

3. Discussion

Under the combined influence of climate change and human activities, Xinjiang's natural grassland NPP showed an overall increasing trend after 2000, but with significant spatiotemporal heterogeneity. The warming-wetting trend in Xinjiang, particularly pronounced since 2000, has generally benefited grassland vegetation growth. However, enhanced interannual precipitation variability has intensified NPP fluctuations, consistent with previous findings on climate extremes in the region.

The spatial pattern of NPP closely mirrors precipitation distribution, decreasing from mountainous areas toward basins. This relationship aligns with studies showing that Xinjiang's grassland productivity is strongly controlled by water-heat dynamics. The higher NPP in northern Xinjiang reflects greater precipitation from Atlantic air masses and orographic effects, while southern Xinjiang's lower productivity results from continental air masses and intensified aridity. The positive NPP-precipitation correlation across most regions underscores precipitation's critical role in grassland growth, particularly in this arid environment.

Since 2000, implementation of the "Returning Grazing Land to Grassland" program and ecological compensation policies has reduced human disturbance, alleviated grassland degradation, and promoted vegetation recovery. These measures, including grazing bans, rotational grazing, and reseedling, have contributed to the observed NPP increases. The consistency between remote sensing observations and policy implementation effects suggests that ecological restoration efforts have been effective in reversing historical degradation trends.

However, the study reveals that climate warming affects northern and southern

Xinjiang differently. Northern Xinjiang' s temperature rise extends the growing season, while southern Xinjiang' s warming increases evapotranspiration demand, potentially exacerbating water stress despite precipitation increases. This asymmetric response highlights the complexity of climate-vegetation interactions across the region.

4. Conclusion

This study utilized MOD17A3HGF NPP data and auxiliary datasets to analyze natural grassland NPP dynamics across multiple spatial scales and its response to climate factors in Xinjiang from 2000 to 2018. The main conclusions are:

- 1) Natural grassland NPP in Xinjiang showed a fluctuating increasing trend, with a multi-year average of $0.103 \text{ kg C} \cdot \text{m}^{-2}$. Spatially, NPP gradually decreased from the Ili River Valley, Tianshan Mountains, Altai Mountains, and Kunlun Mountains toward the Junggar and Tarim Basins.
- 2) Northern Xinjiang' s grassland NPP ($0.149 \text{ kg C} \cdot \text{m}^{-2}$) significantly exceeded that of southern Xinjiang ($0.055 \text{ kg C} \cdot \text{m}^{-2}$), with both regions showing increasing trends. Prefecture-level analysis revealed generally increasing NPP but with distinct interannual variations. Among grassland types, ten of eleven categories showed increasing NPP, while alpine desert remained essentially unchanged.
- 3) Grassland NPP exhibited both positive and negative correlations with temperature, while responses to precipitation were predominantly positive. Positive temperature correlations were mainly distributed on northern Tianshan slopes, whereas positive precipitation correlations concentrated in the Ili River Valley, northern Tianshan slopes, and western Junggar Mountains.

The “asymmetric warming-wetting” trend in Xinjiang—where the region overall becomes warmer and wetter but local areas experience warming-drying—has important implications for grassland management. While climate change and reduced human interference have benefited grassland vegetation, intensified precipitation variability poses challenges for sustainable grassland utilization. These findings provide a scientific basis for grassland health assessment, carbon budget evaluation, and sustainable management strategies in Xinjiang.

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