Effects of Climate Change over the Past 50 Years on Forage Production Potential and Phenology in the Tibetan Plateau (Postprint)

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Abstract

Based on monthly meteorological data of temperature, precipitation, and sunshine hours from 107 meteorological stations on the Qinghai-Tibet Plateau and its surrounding areas during 1965-2013, this study analyzed climate change trends in the Qinghai-Tibet Plateau region since 1965, and employed MODIS data, the Thornthwaite Memorial model, and GIS technology to analyze forage climatic production potential and its spatiotemporal variation characteristics over the past 50 years on the Qinghai-Tibet Plateau. Using continuous 22-year phenological observation data of forage on the Qinghai-Tibet Plateau, the spatiotemporal variation characteristics of forage phenological periods and the relationships between meteorological factors and main forage developmental stages were investigated. The results showed that: 1) The average temperature on the Qinghai-Tibet Plateau exhibited an increasing trend over the past 50 years, with a warming magnitude of 0.53 ℃ (10a) 1; precipitation generally showed an upward trend, but with a small increase magnitude, with a trend rate of 7.81 mm (10a) 1; while sunshine hours showed a decreasing trend, with a decline magnitude of 16.94 h (10a) 1. 2) From 1965 to 2013, forage climatic production potential on the Qinghai-Tibet Plateau generally showed an increasing trend; spatially, it increased sequentially from northwest to southeast, with relatively large increase magnitudes in the northern and southern parts of Qinghai Province, while the increase magnitude was relatively small in eastern Tibet, and there were considerable differences between the northern and southern regions. 3) The green-up period, heading period, and flowering period of forage all showed advancing trends, while the withering period showed a delaying trend, thereby extending the forage phenological period; the forage green-up period gradually delayed from southeast to northwest, while the withering period mainly occurred on days 257-289 of the year, with less obvious overall spatial variation than the green-up period. 4) Both temperature and precipitation were significantly positively correlated with forage phenological periods, while sunshine hours were significantly negatively correlated with them, and temperature was the main factor affecting changes in forage phenological periods. Utilizing the response patterns of forage production potential and phenological periods to climatic factors on the Qinghai-Tibet Plateau can provide references and basis for improving actual forage yield and protecting the grassland ecosystem of the Qinghai-Tibet Plateau.

Full Text

Preamble

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Impact of Climate Change on Potential Productivity and Phenological Phase of Forage in the Qinghai-Tibet Plateau in the Past 50 Years*

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Abstract

Based on monthly temperature, precipitation, and sunshine duration data from 107 meteorological stations on and around the Qinghai-Tibet Plateau from 1965 to 2013, this study analyzed climate change trends in the region since 1965. Using MODIS data, the Thornthwaite Memorial model, and GIS techniques, we examined the spatial and temporal variation characteristics of climate-driven forage production potential on the plateau over the past 50 years. Additionally, using 22 years of continuous observational data on forage growth stages, we investigated the spatiotemporal patterns of forage phenology and the relationship between meteorological factors and key developmental stages. The results indicate: (1) The mean temperature on the Qinghai-Tibet Plateau showed a significant upward trend over the past 50 years, with a warming rate of 0.53 ℃·(10a) ^{1}. Precipitation exhibited an overall increasing trend, albeit with a small magnitude (7.81 mm·(10a) ^{1}), while sunshine duration decreased at a rate of 16.94 h·(10a) ^{1}. (2) From 1965 to 2013, the climate production potential of forage on the plateau generally increased. Spatially, it increased from northwest to southeast, with larger increases in northern and southern Qinghai Province, smaller increases in eastern Tibet, and substantial differences between northern and southern regions. (3) The regreening, heading, and flowering stages of forage showed advancing trends, while the yellowing stage was delayed, thereby extending the phenological period. Regreening stage was progressively delayed from southeast to northwest, whereas the yellowing stage primarily occurred between days 257–289 of the year, showing less pronounced spatial variation than regreening. (4) Both temperature and precipitation showed significant positive correlations with forage phenology, while sunshine duration was significantly negatively correlated, with temperature being the dominant factor influencing phenological changes. These findings provide a scientific basis for improving actual forage yield and protecting the grassland ecosystem of the Qinghai-Tibet Plateau.

Keywords: Qinghai-Tibet Plateau; Climate change; Grassland vegetation; Climate production potential; Phenological period

Introduction

Climate change represents a major global challenge in the 21st century, a scientific fact that has garnered widespread international attention, particularly regarding global warming. The IPCC Fifth Assessment Report indicates that global surface temperatures have continuously risen, increasing by 0.85 ℃ from 1880 to 2012, and that the period 1983–2012 was likely the warmest 30-year interval in the Northern Hemisphere in the past 1,400 years. Climate change significantly influences interannual vegetation dynamics, and grasslands, as the dominant component of terrestrial ecosystems, are highly sensitive to such changes. Global climate change inevitably alters forage growth environments, subsequently affecting growth dynamics, structure, and function. Understanding the impacts of climate change on grassland ecosystems has become a critical research topic in climate change adaptation studies, with particular attention focused on how climate change affects forage production potential, growing seasons, and phenological phases.

Grasslands constitute China' s largest natural ecological barrier, covering one-third of the national land area and primarily distributed in climatically sensitive regions such as the arid and semi-arid areas of Northwest China, the Qinghai-Tibet Plateau, and the Inner Mongolia Plateau. In recent decades, grassland ecosystems have undergone significant changes under the combined influence of global climate change and human activities, severely impacting livestock development and posing serious challenges to national ecological security. The Qinghai-Tibet Plateau contains approximately 1.6×10 km^2 of grassland, accounting for 63.9% of the region' s total area, making it both an important pastoral area and a critical ecological barrier. As a sensitive zone for climate change and a typically fragile ecological environment, the plateau serves as a "driver and amplifier of global climate change," exhibiting sensitive responses and strong influences on global changes. Even slight climatic variations can lead to vegetation structural damage, functional changes, and even vegetation zone shifts. Under significant warming, forage productivity, phenology, and growing seasons have changed markedly in recent decades, affecting both livestock development and national ecological security.

Previous studies have examined these dynamics at regional scales. For instance, Luo et al. used Miami and Thornthwaite Memorial models to analyze spatiotemporal variations in climate production potential in Gansu Province over nearly 40 years, finding a decreasing trend from southeast to northwest and that both warming and increased moisture favored production potential. Duan et al. studied forage regreening and production potential in Yanchi, Ningxia, noting advancing regreening trends and slight increases in climate production potential with rising temperatures and precipitation, though water remained the primary limiting factor. Song et al. monitored vegetation phenology in northern Tibet using remote sensing, revealing delayed regreening from southeast to northwest, less obvious changes in withering stage, and that advanced regreening and extended growing seasons were mainly driven by temperature increases. However, most research has focused on factors affecting climate production potential, with minimal investigation of factors influencing developmental processes and phenology. Therefore, there is an urgent need to understand the spatiotemporal differences in forage production potential, phenology, and growing seasons, and to clarify how these respond to climate change on the Qinghai-Tibet Plateau.

This study addresses this knowledge gap by analyzing monthly temperature, precipitation, sunshine duration, and other meteorological data from 1965–2013, combined with 1992–2013 forage growth stage observations, using MODIS data, the Thornthwaite Memorial model, and GIS techniques to examine spatiotemporal patterns of forage production potential and phenology, and to elucidate relationships between meteorological factors and key developmental stages. The findings aim to provide scientific guidance for protecting the plateau’ s grassland ecosystems and informing livestock production.

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1. Study Area Overview

The Qinghai-Tibet Plateau is located between 28°32 –40°01 N and 78°27 –104°43 E, covering an area of 2.3×10 km^2. This study encompasses the entire Tibet Autonomous Region and Qinghai Province, western Sichuan, southern Xinjiang, and parts of Gansu and Yunnan. With an average elevation exceeding 4,000 m, the region features complex and diverse climate types: warm-humid conditions in the southeast and cold-arid conditions in the northwest. Most areas have mean annual temperatures below 0 ℃, with the warmest month averaging 5.5–13.6 ℃. Precipitation is primarily controlled by the southwest monsoon, with annual totals exceeding 400 mm in the southeast but less than 100 mm in the northwest, decreasing from southeast to northwest with highly uneven seasonal distribution and distinct wet and dry seasons.

As the world’ s “Third Pole,” the plateau hosts rich vegetation types, though grassland degradation has become severe in recent years, with degraded areas accounting for one-third of total grassland area. Major grassland vegetation types include alpine shrub meadow, alpine steppe, alpine desert, and alpine meadow vegetation. Alpine meadows are mainly distributed in the eastern plateau at elevations of 3,200–5,200 m, with mean annual temperatures below 0 ℃ and precipitation of 400–700 mm. Alpine steppe occurs primarily in the central-western plateau and in the Kunlun and Qilian Mountains, characterized by high elevation, cold, and arid conditions. Temperate steppe is mainly found in the Huangshui River basin in the eastern plateau, with relatively higher temperatures and annual precipitation around 350 mm.

2.1 Data Sources

Meteorological data were obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn), including monthly mean temperature, precipitation, and sunshine duration from 107 meteorological stations on and around the Qinghai-Tibet Plateau from 1965–2013 [Figure 1: see original paper], as well as forage developmental stage data from the Chinese Crop Growth and Soil Moisture Dataset at ten-day intervals for 1991–2013.

2.2.1 Climate Change Trend Analysis on the Qinghai-Tibet Plateau

The forage growing season on the plateau typically spans April–October. Growing season mean temperature, precipitation, and sunshine duration were calculated by averaging or summing daily data from April–October for each station. Missing data were interpolated using linear interpolation or averaging methods, with all trend equations fitted using linear regression. Effective accumulated temperatures 0 ℃ and 5 ℃ during the growing season were calculated using the same methods as precipitation and sunshine duration. Spatial distributions of meteorological elements were mapped using GIS interpolation techniques.

To further understand how climate factors (temperature, precipitation, sunshine duration) affect different forage growth stages, this study analyzed not only the spatiotemporal changes in accumulated temperature, precipitation, and sunshine duration during the growing season over the past 50 years, but also examined climate trends during key forage growth periods.

2.2.2 Forage Production Potential Estimation

Forage production potential is determined by the combination of genetic traits and environmental conditions during the growth period. Under constant other factors, climate conditions during the growth period have the greatest impact on yield formation. To analyze the spatiotemporal patterns of forage climate production potential, this study employed the Thornthwaite Memorial model:

$$T_{spv} = 1.05 \times \frac{V}{L} \times \left(1 - \frac{0.316}{L}\right)^{0.316}$$

where T_{spv} is climate production potential (g·m ^{2}·a ^{1}), V is mean annual actual evapotranspiration (mm), L is mean annual potential evapotranspiration (mm), and T is mean annual temperature (℃), representing an empirical function of mean annual temperature; P is mean annual precipitation (mm).

2.2.3 Forage Phenology Estimation

Forage typically begins development when daily mean temperature reaches 5 ℃. Growing season length was calculated as the number of days from April–October when daily temperature exceeded 5 ℃. Forage regreening, flowering, heading, and yellowing stages were determined using observational data from the 107 meteorological stations for 1991–2013, with missing data interpolated using linear methods. Phenological parameters were retrieved using threshold methods based on NDVI time series, where specific thresholds between maximum and minimum NDVI values within each growing season were established. The timing when NDVI values reached corresponding thresholds during the ascending phase was designated as regreening stage, while timing during the descending phase was designated as yellowing stage.

3.1.1 Climate Change Trends Over the Past 50 Years

Over the past 50 years, mean temperature on the Qinghai-Tibet Plateau showed an increasing trend with a warming rate of 0.53 ℃·(10a) ^{1}. Trend analysis revealed that temperatures remained below the long-term average during 1965–1986, increased during 1987–1997, and showed accelerated warming after 1998 [Figure 2a: see original paper]. Precipitation exhibited an overall upward trend with a small increase rate of 7.81 mm·(10a) ^{1}, with the most pronounced variation occurring during 1997–1998 when precipitation reached its maximum [Figure 2b: see original paper]. Sunshine duration decreased over the 50-year period at a rate of 16.94 h·(10a) ^{1}, peaking at 2,780 h in 1986 and reaching its minimum of 2,584 h in 1988 [Figure 2c: see original paper].

Natural grasslands on the plateau are dominated by Poaceae species, with growth stages including regreening, heading, flowering-maturity, and yellowing. The main growing season extends from April–October each year, with regreening beginning in late March and ending in June, maturity occurring in mid-to-late August, and yellowing in September–October.

As shown in [Figure 3: see original paper], the mean temperature during the forage growing season increased over the past 50 years at a rate of 0.48 ℃·

(10a) ^{1}, exceeding China’ s average surface warming rate of 0.22 ℃·(10a) ^{1} and the global/Northern Hemisphere rate of 0.13 ℃·(10a) ^{1}, indicating pronounced warming in this region. Interannual temperature variations show continuous warming from the 1960s to the 21st century, consistent with global warming trends. Growing season precipitation increased at a rate of 0.34 mm·(10a) ^{1}, with relatively small changes suggesting natural climatic oscillations. Since 1991, the region has experienced a dry period, particularly since 2001 when precipitation declined markedly, indicating intensifying drought. Precipitation was relatively low during 1965–1994, increased significantly during 1995–2004, then declined again after 2005. Growing season sunshine duration decreased overall at a rate of -23 h·(10a) ^{1}, showing an increasing trend from the mid-1960s to mid-1980s, followed by a clear decreasing trend thereafter.

On the plateau, snowmelt and soil thawing begin when daily mean temperature 0 ℃, with alpine meadow plants starting to germinate; active growth of cool-season forage occurs when temperature 5 ℃. Therefore, accumulated temperatures 0 ℃ and 5 ℃ can characterize growth patterns of major plateau plants. Spatial distribution maps [Figure 4: see original paper] show that accumulated temperatures 0 ℃ and 5 ℃ increase gradually from northwest to southeast, with most areas showing significant increasing trends. Higher accumulated temperatures (>2,000 ℃) occur in the southeastern and northeastern plateau, including Gannan Tibetan Autonomous Prefecture in Gansu, Sichuan, Yunnan, and parts of Tibet. Lower values are found in the western and central regions, including southern Qinghai, Guoluo, Nagqu, and the Qiangtang area, where accumulated temperature 5 ℃ in northern Tibet and southwestern Qinghai reaches only 1,500 ℃.

Precipitation distribution [Figure 5: see original paper] shows increasing amounts from the northwestern interior to the Yarlung Zangbo River valley in the southeast. Areas in northwestern Tibet, Ga’ er County in the northwestern plateau, and the Qaidam Basin in Qinghai are relatively dry with <400 mm precipitation, unsuitable for forage growth. Central regions have insufficient precipitation for forage water requirements but can support forage cultivation with irrigation. Southeastern areas such as Aba and Garzê in Sichuan receive >400 mm precipitation, meeting forage water demands. Overall, northwestern plateau regions exhibit warming-drying trends due to rising temperatures and decreasing precipitation, while southeastern areas show warming-wetting trends. Sunshine duration distribution [Figure 5: see original paper] shows lower values in the southeastern plateau, gradually increasing toward the northwest. Low-value areas around Zedang Town and Linzhi County in southern Tibet receive ~1,850 h, central areas ~2,200 h, while the highest values occur in Ga’ er County, Tibet, and the Qaidam region of Qinghai, reaching ~3,000 h.

3.1.3 Climate Trends During Key Forage Growth Stages

Regreening and heading-flowering stages are critical production periods, typically requiring higher temperatures and precipitation but lower sunshine duration than the regreening stage. Over the past 50 years, mean temperature during key growth stages increased, with regreening stage warming at 3.4 ℃ · (10a) ^{1} and heading-flowering stage at 0.7 ℃ · (10a) ^{1} [Figure 6a: see original paper]. Precipitation during both regreening and heading-flowering stages increased, though with small magnitudes (127.3 mm · (10a) ^{1} and 22.0 mm · (10a) ^{1}, respectively) [Figure 6b: see original paper]. Sunshine duration showed a decreasing-increasing-decreasing pattern during this period. Temperatures were relatively high during the flowering-maturity stage from the mid-1960s to mid-1970s, then decreased before increasing again from the mid-1970s to the 21st century, while precipitation showed a decreasing-increasing-decreasing trend. Sunshine duration increased from the mid-1960s to mid-1980s, then decreased significantly after the mid-1980s. Overall, sunshine duration during key growth stages declined, with regreening stage decreasing at -350.0 h · (10a) ^{1} and heading-flowering stage at -179.6 h · (10a) ^{1} [Figure 6c: see original paper].

3.2 Spatiotemporal Variation of Forage Production Potential

As shown in [Figure 7a: see original paper], forage climate production potential on the Qinghai-Tibet Plateau showed an overall increasing trend over the past 50 years, with a small increase of 136.7 g · m ^{2} per decade and a multi-year average of 706 g · m ^{2} · a ^{1} (range: 620–760 g · m ^{2} · a ^{1}). Interannual variations indicate larger increases from the mid-1960s to mid-1990s, though values remained below the long-term average, while values since the mid-1990s have exceeded the average but with slower increases [Figure 7b: see original paper].

Spatial distribution reveals significant differentiation, increasing from northwest to southeast. High-value areas in southeastern Tibet, Sichuan, and Yunnan reach maximum values of 1,168 g · m ^{2} · a ^{1}, while low-value areas in northwestern Qinghai have minimum values of only 4 g · m ^{2} · a ^{1}, with substantial differences between northern and southern regions [Figure 8a: see original paper]. Compared with 1965–1974, the period 2004–2013 saw larger increases in western Sichuan, eastern Tibet, Yunnan, and areas in southern Qinghai, Guoluo, Nagqu, and Qiangtang, while smaller increases occurred in northwestern Tibet, Qaidam, and the eastern Qilian Mountains of Qinghai [Figure 8b: see original paper]. Comparison between these periods shows increased climate production potential across most of the plateau, with particularly significant increases in central regions (150–250 g · m ^{2} · a ^{1}). However, some areas in southeastern Tibet, northern Qaidam, and northwestern Tibet experienced decreases due to temperature and precipitation effects, with the most significant decline (~500 g · m ^{2} · a ^{1}) in Linzhi, Tibet.

3.3.1 Trends in Forage Phenology

Natural phenological changes are comprehensive indicators of climate and environmental change, providing the most direct botanical signals of climate change. Forage typically begins development at 5 ℃ daily mean temperature. Recent warming has accelerated forage developmental processes. As shown in [Figure 9: see original paper], regreening stage showed an advancing trend at a rate of -7.4 d • (10a) ^{1} (7–8 days earlier per decade). Heading and flowering stages also advanced (-6.2 d • (10a) ^{1} and -6.4 d • (10a) ^{1}, respectively), while yellowing stage was delayed at 2.1 d • (10a) ^{1} (2–3 days later per decade). Overall, climate change over the past 50 years has extended the forage growing season by 11.2 d • (10a) ^{1} (11–12 days per decade). Significance testing shows that growing season length had the most significant trend, followed by regreening stage, while yellowing stage showed weaker significance.

3.3.2 Spatial Variation in Forage Phenology

Forage regreening on the plateau typically begins in late March and continues through June, occurring between days 129–177 of the year, with progressive delay from southeast to northwest. In lower-elevation valley areas in the southeast, regreening occurs before day 129, while higher-elevation areas (such as the source regions of the Yellow River, Yangtze River, and Yarlung Zangbo River) regreen after day 177. Overall, regreening in lower-elevation eastern valleys begins in mid-to-late April, delaying with increasing elevation and westward expansion. For example, in Nagqu County, southeastern areas regreen in early May, central-northern areas and most of Amdo and Nyainrong in mid-May, while Xainza and Baingoin in the west regreen in early-to-mid May or late May and beyond. Most areas in Nima and Shuanghu regreen in late May, while Kunlun Mountain areas are delayed until June [Figure 10a: see original paper]. Interannual spatial variation shows regreening advancing across most of the plateau from east to west with elevation, with magnitude of 1–10 days. Areas with advanced growing season start are concentrated in central and southeastern plateau, mainly in Guoluo, Nagqu, and eastern Tibet, closely related to combined effects of increased rainfall and warming [Figure 10c: see original paper]. Delayed regreening areas are distributed in southeastern Baingoin, southern Xainza, Nima, and central-southern Nagqu.

The yellowing stage shows less obvious spatial patterns compared to regreening [Figure 10b: see original paper]. Yellowing primarily occurs between days 257–289 of the year, with relatively concentrated timing in Tibet Autonomous Region and Qinghai Province, though some areas begin yellowing in October. In the Sichuan Basin, yellowing occurs in late October, associated with abundant precipitation and vigorous forage growth. Most eastern plateau areas yellow in mid-to-late October, while forage around Selin Co Lake yellows in late October or even November. Central plateau areas including Guoluo, Nagqu, Amdo, Xainza, Nyainrong, and Baingoin begin yellowing in early October, while northwestern areas start in September. Spatial variation in yellowing is concentrated in Tibet and Qinghai, with small magnitude. Areas with advanced yellowing include Baqên, Sog County, Amdo, the Sichuan Basin, and Yunnan, while delayed areas are mainly in southern Qinghai plateau, Kunlun alpine desert zones, and central Nima [Figure 10d: see original paper].

3.3.3 Spatial Variation in Forage Growing Season

Due to the plateau' s large area and complex topography, regional differences in temperature and precipitation create distinct spatial patterns in growing season length. Central plateau areas including southern Qinghai, Guoluo, Nagqu, and Qiangtang have shorter growing seasons, while southern Tibet has longer seasons, typically 120-190 days. Comparison between 2004-2013 and 1965-1974 shows regional variations, with extended growing seasons in western Tibet and shortened seasons in Qaidam, eastern Qilian Mountains in Qinghai, Guoluo-Nagqu, eastern Tibet, and Yunnan. However, due to significantly advanced regreening and delayed yellowing, the overall trend is toward longer growing seasons. As shown in [Figure 11: see original paper], the largest increases occurred in Nyalam and Tingri in Tibet, while the largest decreases occurred in parts of Sichuan. These differences reflect varying influences of temperature and precipitation on natural forage growth across regions. Previous studies have shown that in semi-humid areas, heat conditions are the main factor affecting regreening, while in arid and semi-arid areas, regreening timing is primarily constrained by water availability. Consequently, the relationship between phenology and geographic location becomes unstable under climate change, and the effects of these two climate factors are interdependent rather than independent. Temperature effects on phenology exhibit temporal lags, and phenological responses to temperature changes are nonlinear.

3.4 Impact of Climate Factors on Forage Phenology

Correlation analysis between forage phenology and climate factors (temperature, precipitation, sunshine duration) during the growing season and key growth stages over the past 50 years reveals several key relationships :

1. **Temperature** is the most critical factor affecting phenology, with a correlation coefficient of 0.942, followed by precipitation (r = 0.428), both significant at the 0.01 level. Warming enhances enzyme activity and accelerates phenological processes, making phenology closely linked to thermal conditions, particularly temperatures preceding each developmental stage.

Studies by Qi et al. and Zhang et al. similarly identified heat conditions as the primary factor affecting regreening, flowering, maturity, and yellowing stages of Poaceae species such as *Stipa capillata* and *Poa annua* in Qinghai. **Precipitation** is another important factor, as drought delays development and postpones phenological stages. **Sunshine duration** is significantly negatively correlated with phenology ($r = -0.527$, $p < 0.01$). Further analysis indicates that increasing temperature and precipitation raise atmospheric water vapor pressure, reducing sunshine duration and significantly delaying phenology, consistent with earlier phenology analysis results. Thus, temperature and precipitation are key factors affecting phenology and also mediate the negative correlation between sunshine duration and phenology.

2. During the growing season, phenology is positively correlated with temperature ($r = 0.937$) and precipitation ($r = 0.293$), and negatively correlated with sunshine duration ($r = -0.582$, $p < 0.01$). Sunshine duration is an important factor because plants contain phytochrome, which is involved in many developmental stages. Reduced photoperiod can promote flowering and advance phenology, while extended photoperiod has the opposite effect.
3. During the heading-flowering stage, temperature remains the most critical factor ($r = 0.816$), followed by precipitation ($r = 0.385$, $p < 0.01$), while sunshine duration is negatively correlated ($r = -0.376$, $p < 0.01$).

4. Discussion and Conclusions

This study used the Thornthwaite Memorial model to estimate forage climate production potential on the Qinghai-Tibet Plateau over the past 50 years, revealing an overall increasing trend [136.7 g · m ^{2} · (10a) ^{1}] with small magnitude. Under global warming with sharp temperature increases but small precipitation changes, the degree of water-heat coordination has weakened. In this context, warming increases surface evaporation, reducing water availability for vegetation. However, due to high elevation, thin air, and relatively abundant sunshine with strong radiation, reduced sunshine duration decreases evapotranspiration, conserving moisture and promoting forage growth. Therefore, changes in production potential are complex, depending on combined effects of light, temperature, and water. Spatially, production potential increases from northwest to southeast, with high values in southeastern Tibet, Sichuan, and Yunnan, and low values in northwestern Qinghai, showing large north-south differences. This pattern reflects that warming intensifies drought in northern areas, making forage growth more water-dependent, while increasing vegetation growth cycles and productivity in southern humid regions.

Second, this study examined forage phenological changes, showing good comparability with Song et al.’ s research on spatiotemporal dynamics of vegetation phenology in northern Tibet using dynamic threshold methods. Qi et al. found that temperature was the main factor affecting vegetation regreening, yellowing, and growing season length at most stations in Qinghai, with precipitation and sunshine duration only relevant at individual stations. Song et al. similarly found that interannual temperature variation and warming trends directly affected advanced regreening and extended growing seasons, while precipitation had less impact. However, Zhang et al. found that precipitation in the previous autumn and current spring also significantly affected phenological changes in Qinghai. This study, based on MODIS data and 22 years of continuous observations, analyzed spatiotemporal patterns of forage phenology and its relationship with meteorological factors, confirming temperature as the most critical factor, precipitation as another important factor, and sunshine duration as significantly negatively correlated. Forage regreening, heading, and flowering stages showed advancing trends [-7.4 d · (10a) ^{1}, -6.2 d · (10a) ^{1}, -6.4 d · (10a) ^{1}], while yellowing stage was delayed [2.1 d · (10a) ^{1}], resulting in an extended growing season [11.2 d · (10a) ^{1}]. Growing season extension, particularly advanced regreening, is considered a major contributor to enhanced carbon sink function in northern mid- and high-latitude regions. For the alpine grasslands of the Qinghai-Tibet Plateau, extended growing seasons can increase carbon sequestration, reduce atmospheric CO accumulation, slow warming rates, and significantly impact livestock production and ecological security. Spatially, regreening occurs between days 129–177, delaying from southeast to northwest, while yellowing occurs between days 257–289.

Due to sparse meteorological stations in northwestern regions, several southern Xinjiang stations were included to improve spatial interpolation accuracy. This study used the Thornthwaite Memorial model to simply estimate forage production potential, revealing spatiotemporal patterns, though as an empirical model it can only roughly characterize spatial patterns rather than precisely describe evolutionary trends. Future research should employ process-based models or remote sensing methods for in-depth investigation of spatiotemporal patterns and driving mechanisms. Additionally, limited phenological observation data restricted this study to simple characterization of phenological patterns; future work should analyze spatiotemporal changes in different forage types across different regions, focusing on climate change impacts on typical forage phenology on the plateau.

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