

Effects of climate change and human activities on grassland productivity: A case study of the Qinghai Lake Basin, China Postprint

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Date: 2025-07-17T00:00:00+00:00

Abstract

Grassland is a key component of the ecosystem in the Qinghai Lake Basin, China. Understanding the effects of climate change and human activities on grassland productivity significantly improves ecological conservation and promotes sustainable vegetation growth in this area. Based on the net primary productivity (NPP) products of MOD17A3HGF (a moderate-resolution imaging spectroradiometer (MODIS) product that provides annual NPP at 500 m resolution) and meteorological data, we analyzed the spatial and temporal evolution of grassland NPP and its interaction with climate factors in the Qinghai Lake Basin from 2001 to 2022 via partial correlation and trend analysis methods. We also used the deflecting trend residual method and scenario analysis method to quantitatively assess the relative contributions of climatic factors and human activities to grassland NPP. The results revealed that: (1) during the past 22 a, grassland NPP increased considerably, with a gradient change from the northwest to the southeast of the study area; (2) sunshine duration, precipitation, and temperature positively influenced grassland NPP, with sunshine duration exerting a stronger effect on grassland NPP than precipitation and temperature; and (3) 98.47% of the grassland in the study area was restored, with an average contribution of 65.00% from human activities and 35.00% from climatic alterations. Compared with climate change, human-induced factors had a greater effect on grassland NPP in this area. The results of the study not only provide important scientific support for ecological restoration and sustainable development of the basin but also offer new ideas for research on similar ecologically fragile areas.

Full Text

Preamble

Journal of Arid Land (2025) 17(7): 997-1013

doi: 10.1007/s40333-025-0022-x; CSTR: 32276.14.JAL.0250022x

Science Press & Springer-Verlag

Effects of Climate Change and Human Activities on Grassland Productivity: A Case Study of the Qinghai Lake Basin, China

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Abstract: Grassland is a key component of the ecosystem in the Qinghai Lake Basin, China. Understanding the effects of climate change and human activities on grassland productivity significantly improves ecological conservation and promotes sustainable vegetation growth in this area. Based on the net primary productivity (NPP) products from MOD17A3HGF (a moderate-resolution imaging spectroradiometer (MODIS) product that provides annual NPP at 500 m resolution) and meteorological data, we analyzed the spatial and temporal evolution of grassland NPP and its interaction with climate factors in the Qinghai Lake Basin from 2001 to 2022 via partial correlation and trend analysis methods. We also used the detrending trend residual method and scenario analysis method to quantitatively assess the relative contributions of climatic factors and human activities to grassland NPP. The results revealed that: (1) during the past 22 years, grassland NPP increased considerably, with a gradient change from the northwest to the southeast of the study area; (2) sunshine duration, precipitation, and temperature positively influenced grassland NPP, with sunshine duration exerting a stronger effect than precipitation and temperature; and (3) 98.47% of the grassland in the study area was restored, with an average contribution of 65.00% from human activities and 35.00% from climatic alterations. Compared with climate change, human-induced factors had a greater effect on grassland NPP in this area. These results not only provide important scientific support for ecological restoration and sustainable development of the basin but also offer new ideas for research on similar ecologically fragile areas.

Keywords: ecological conservation; human-induced factors; net primary productivity; precipitation; temperature

Citation: ZHANG Jinlong, MA Xiaofang, QI Yuan, YANG Rui, LI Long, ZHANG Juan, MA Chao, WANG Lu, WANG Hongwei. 2025. Effects of climate change and human activities on grassland productivity: A case study of the Qinghai Lake Basin, China. *Journal of Arid Land*, 17(7): 997-1013. <https://doi.org/10.1007/s40333-025-0022-x>; <https://cstr.cn/32276.14.JAL.0250022x>

1 Introduction

Grassland ecosystems serve both ecological and productive functions and constitute 37.00% of the Earth's land surface (O' Mara, 2012; Wang et al., 2019; Bardgett et al., 2021). The Qinghai Lake Basin is an important animal husbandry production base in Qinghai Province, China, where grassland resources account for more than 70.00% of the basin area. Since 1977, due to climatic factors and human-induced disturbances, grasslands in the Qinghai Lake Basin have degraded over large areas (Yuan et al., 2018). The "Western Development Strategy" has considerably altered this situation, leading to a notable shift from degradation to improvement in the grasslands of this area (Lan and Li, 2022; Wang et al., 2024a). However, the precise effects of climate change and human activities on grassland ecosystems in this area need to be elucidated, along with the identification of grasslands that have either recovered or declined.

Net primary productivity (NPP) is an important metric for evaluating the productivity of grassland ecosystems and determining their ecological well-being (Zhao et al., 2022; Zheng et al., 2024). The spatiotemporal dynamics of NPP are regulated by complex interplay between natural processes and human effects, with climate variability and human interventions emerging as predominant driving forces (Qi et al., 2020; Qu et al., 2020; Teng et al., 2020; Zhang et al., 2020; Zhou et al., 2020; Xie et al., 2022; Shi et al., 2023). Variations in NPP are greatly affected by factors that regulate plant metabolism or change land use patterns. Different statistical techniques, such as regression modeling, residual analysis, geographic detector, and partial derivative computation, are extensively used to evaluate the effect of various factors on NPP (Guan et al., 2019; Li et al., 2023; Wang et al., 2023). We selected the partial derivative analysis method in this study to quantitatively analyze NPP for several reasons. First, this method comprehensively considers the physiological and ecological mechanisms of vegetation (Yan et al., 2019). Second, this approach requires a minimal set of parameters that can be easily obtained (Liu and Sun, 2016). Additionally, climatic factors and vegetation productivity often exhibit complex non-linear relationships. The partial derivative analysis method can capture these non-linear dynamics, thereby more accurately assessing the effects of various factors on NPP (Qu et al., 2020).

Several studies on grassland productivity in the Qinghai Lake Basin have focused on the geographic and temporal trends of NPP and how they relate to various

driving factors. For example, Qiao and Guo (2016) used the Carnegie-Ames-Stanford-Approach (CASA) model along with remote sensing data to simulate and analyze the spatiotemporal patterns of grassland NPP in the Qinghai Lake Basin from 2001 to 2011. Li et al. (2023) systematically analyzed the spatiotemporal patterns of vegetation NPP in the basin via moderate-resolution imaging spectroradiometer (MODIS) NPP data and revealed that the interactive effects of temperature, elevation, and human activities were the main drivers of changes in NPP. However, studies quantifying the relative contributions of climate fluctuations and human activities to variations in NPP in grassland ecosystems remain limited (Wang et al., 2021; Zhang et al., 2023). While previous studies have identified temperature and precipitation as key climatic factors influencing grassland NPP changes in the Qinghai Lake Basin (Guo et al., 2014), a significant gap exists in the quantitative analysis of the relative contributions of human activities and climate change.

Based on the above background, we used slope, partial correlation, partial derivative, and scenario analyses to assess the spatiotemporal evolution characteristics of grassland NPP from 2001 to 2022. Our findings may reveal the interplay between climatic factors and grassland NPP, quantify the effect of climate change and human effects, and lay a robust foundation for the sustainable management and conservation of grasslands in the Qinghai Lake Basin.

2.1 Study Area

The Qinghai Lake Basin is located in the northeastern Qinghai-Xizang Plateau (36°15' 38°20' N, 97°40' 101°05' E), encompassing an area of 29.6×10^3 km² (Fig. 1 [Figure 1: see original paper]). From 1958 to 2018, the basin had an annual average temperature of -3.93°C and average annual precipitation of 372.43 mm. These climatic variables exhibited a geographical distribution, with higher values in the eastern parts and lower values in the western parts (Wang et al., 2022a). Grassland is the main vegetation type in this area (Wang et al., 2016).

Fig. 1 Overview and distribution of grasslands in the Qinghai Lake Basin

2.2 Data

Data on NPP were obtained from the MOD17A3HGF product (a MODIS product that provides annual NPP at 500 m resolution; <https://lpdaac.usgs.gov>) from 2001 to 2022. NPP verification data from 2000 to 2017 with a spatial resolution of 1 km were derived from the productivity dataset of the Xizang Plateau calculated by Niu and Zhang (2021) using the CASA model.

Meteorological data, including average temperature, sunshine duration, and precipitation data from 2001 to 2022, were derived from the Daily Climate Observation of China's ground-based stations (<http://data.cma.cn>). The temperature and precipitation data were validated using monthly scale mean temperature

products from 1901 to 2023 with a 1-km spatial resolution and corresponding monthly scale precipitation data from 1901 to 2023 for China (Peng, 2020). To determine the duration of sunshine, we used a 1-km spatial resolution sunshine duration dataset from 1981 to 2020 retrieved from the Earth Resources Data Cloud (GRDC).

The grazing pressure index data from 2000 to 2019 with a 250-m resolution were obtained from the National Tibetan Plateau/Third Pole Environment Data Center (Liu, 2021). The CO₂ concentration data from 2002 to 2012 were simulated and predicted by Hou et al. (2022). To maintain the precision of the findings, we registered the raster data to the WGS-1984-Albers coordinate system, with the spatial resolution standardized to 500 m.

2.3.1 Australian National University Spline (ANUSPLIN)

ANUSPLIN is a specialized interpolation technique established on the thin-disk spline function, representing an advanced and innovative extension of the conventional multivariate linear regression model. This method not only allows the introduction of covariates (such as elevation) but also handles the spatial interpolation of multiple surfaces simultaneously (Bates et al., 1987).

We used the three-variable local thin-disk smoothing spline method to interpolate daily meteorological data (sunshine duration, air temperature, and precipitation) from 78 weather stations encompassing this basin and its adjacent area from 2001 to 2022, generating monthly meteorological grid products with a 500-m spatial resolution. The equation is as follows:

$$Z_i = f(x_i) + \sum_{j=1}^b y_{ij}\beta_j + e_i, \quad i = 1, 2, \dots, n$$

where Z_i is the response variable at spatial location i ; $f(x_i)$ is the unknown smooth function to be estimated about x_i ; x_i is an independent variable; b is the dimension coefficient; T is the number of iterations; y_i is an independent covariate; e_i is the stochastic error; and n is the number of observations.

2.3.2 Trend Analysis of Slope

Trends in NPP and associated climatic factors were simulated at the pixel scale using the univariate linear regression method (Yin et al., 2020):

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

where n is the number of research years; j is the sequence number of the year; P_j is the values of NPP or meteorological factors corresponding to year j ; and

slope is the change rate, with a positive value indicating an increasing trend and a negative value indicating a decreasing trend. The statistical significance ($P < 0.05$) of the trend analysis was evaluated by conducting the F-test.

2.3.3 Partial Correlation Between NPP and Climate Factors

Partial correlation overcomes the limitations of single correlation analysis, particularly in multivariate scenarios, by isolating the relationships between variables while considering the effects of additional variables (Kim, 2019; Yan et al., 2021). The formula is as follows:

$$r_{mk \cdot z} = \frac{r_{mk} - r_{kz} \times r_{mz}}{\sqrt{(1 - r_{kz}^2)(1 - r_{mz}^2)}}$$

where $r_{mk \cdot z}$ is the partial correlation coefficient between the variables m and k when the variable z is regarded as a constant; r_{mk} , r_{kz} , and r_{mz} are the correlation coefficients between m and k , k and z , and m and z , respectively; m_i and k_i are the values of NPP and meteorological elements, respectively; \bar{m} is the multiyear average NPP; and \bar{k} is the multiyear average of meteorological elements.

2.3.4 Assessing the Contributions of Climate Factors and Human Activities to Changes in Grassland NPP

Following the method described by Xu et al. (2023), we evaluated the relative contributions of climatic and human factors to the recovery and degradation of grasslands by considering six scenarios of changes in NPP (Table 1) and the second-order partial derivative analysis method. The equations are as follows:

$$\text{NPP}_{\text{slope}} = \text{SH} + \text{SC}$$

$$\text{KH} = \frac{\text{SH}}{\text{NPP}_{\text{slope}}} \times 100\%$$

$$\text{KC} = \frac{\text{SC}}{\text{NPP}_{\text{slope}}} \times 100\%$$

$$\text{SC} = S_{\text{tem}} + S_{\text{pre}} + S_{\text{ssd}}$$

$$S_{\text{tem}} = \frac{\partial \text{NPP}}{\partial \text{tem}} \times \frac{d\text{tem}}{dt}$$

$$S_{\text{pre}} = \frac{\partial \text{NPP}}{\partial \text{pre}} \times \frac{d\text{pre}}{dt}$$

$$S_{\text{ssd}} = \frac{\partial \text{NPP}}{\partial \text{ssd}} \times \frac{d\text{ssd}}{dt}$$

where $\text{NPP}_{\text{slope}}$ is the slope of NPP; SH and SC are the contributions of human activities and climatic factors to the changes in grassland NPP, respectively; KH and KC are the relative contribution rates of human activities and climatic factors, respectively; S_{tem} , S_{pre} , and S_{ssd} are the contributions of temperature, precipitation, and sunshine duration to the changes in grassland NPP, respectively; $\partial \text{NPP}/\partial \text{tem}$, $\partial \text{NPP}/\partial \text{ssd}$, and $\partial \text{NPP}/\partial \text{pre}$ are the coefficients of partial correlation between temperature and NPP, between sunshine duration and NPP, and between precipitation and NPP, respectively; and $d\text{tem}/dt$, $d\text{ssd}/dt$, and $d\text{pre}/dt$ are the yearly rates of change in temperature, solar radiation, and precipitation, respectively.

Table 1 Six scenarios of grassland restoration and degradation

Scenario	$\text{NPP}_{\text{slope}}$	SH	SC	Note
BCH	>0	>0	>0	Grassland restoration co-dominated by human activities and climatic factors
BH	>0	>0	<0	Rehabilitation chiefly driven by human activities
BC	>0	<0	>0	Rehabilitation chiefly driven by climatic factors

Scenario	NPP_{slope}	SH	SC	Note
DCH	<0	<0	<0	Grassland degradation co-dominated by human activities and climatic factors
DH	<0	<0	>0	Degradation chiefly driven by human activities
DC	<0	>0	<0	Degradation chiefly driven by climatic factors

Note: NPP_{slope} is the slope of net primary productivity (NPP); SH and SC are the contributions of human activities and climatic factors to the changes in grassland NPP, respectively. $NPP_{\text{slope}} > 0$ indicates grassland restoration; $NPP_{\text{slope}} < 0$ indicates grassland degradation. The abbreviations are the same as in Figure 8 [Figure 8: see original paper].

3.1 Changes in Spatiotemporal NPP

The NPP in the Qinghai Lake Basin had a mean value of 247.650 g C/(m² · a) over the study period, indicating a gradient increasing pattern from northwest to southeast. Areas with NPP less than 200.000 g C/(m² · a) constituted 31.34% of the entire grassland area, mostly clustered in northern and northwestern Tianjun County. Areas with NPP of 200.000–300.000 g C/(m² · a) encompassed 39.17%, predominantly situated in eastern Tianjun County, northern Gangcha County, and the northeastern lakeshore. Areas where NPP exceeded 300.000 g C/(m² · a) accounted for 29.49% of the entire grassland area, predominantly dispersed around the lake zone, with the highest NPP values recorded on the southwestern coast (Fig. 2 [Figure 2: see original paper]).

From 2001 to 2022, NPP increased across 96.42% of the grassland area, with 85.19% of the grassland area showing significant increase ($P < 0.05$). In contrast, only 3.58% of the grassland area experienced a decline in NPP, of which 2.73% decreased significantly ($P < 0.05$). The average annual increase in grassland NPP was $2.520 \text{ g C}/(\text{m}^2 \cdot \text{a})$ from 2001 to 2022. From 2001 to 2014, NPP experienced a faster growth rate of $4.120 \text{ g C}/(\text{m}^2 \cdot \text{a})$, but this rate decreased to $2.830 \text{ g C}/(\text{m}^2 \cdot \text{a})$ from 2015 to 2022 (Figs. 3 and 4 [Figure 3: see original paper] [Figure 4: see original paper]).

3.2 Inter-Annual Changes in Climatic Factors and Their Effects on NPP

The annual average temperature in the Qinghai Lake Basin from 2001 to 2022 ranged from -2.55°C to -0.82°C , with an average of -1.77°C . From 2001 to 2013, temperature in this area did not fluctuate significantly; from 2013 to 2019, temperature increased at a rate of $0.10^\circ\text{C}/\text{a}$; from 2019 to 2022, temperature fluctuated (Fig. 5a [Figure 5: see original paper]).

The average annual precipitation of the basin from 2001 to 2022 ranged from 315.96 to 534.83 mm, with an average of 412.03 mm and a slight increase rate of $1.80 \text{ mm}/\text{a}$ ($P < 0.05$). The change in precipitation occurred in three phases: from 2001 to 2009, precipitation increased consistently with an annual rate of $14.10 \text{ mm}/\text{a}$; from 2010 to 2017, precipitation first decreased and then increased with an annual rate of $18.80 \text{ mm}/\text{a}$; from 2017 to 2022, precipitation decreased at a rate of $8.80 \text{ mm}/\text{a}$ (Fig. 5b [Figure 5: see original paper]).

Over the past 22 years, sunshine duration in the basin ranged from 2683.25 to 2925.47 h, with an average of 2831.18 h, decreasing at a rate of $0.70 \text{ h}/\text{a}$ ($P < 0.05$). From 2001 to 2012, sunshine duration decreased by $15.50 \text{ h}/\text{a}$; from 2013 to 2022, the decreasing trend slowed to $0.10 \text{ h}/\text{a}$ (Fig. 5c [Figure 5: see original paper]).

The degree of influence of climate variables on grassland NPP was further quantified using the trend residual method based on partial derivatives. From 2001 to 2022, the relative contributions of sunshine duration, precipitation, and temperature to NPP were 0.690, 0.170, and $0.007 \text{ g C}/(\text{m}^2 \cdot \text{a})$, respectively. Temperature positively affected NPP changes across 98.25% of the area, with a greater positive effect found in the central area of Gangcha County, whereas the negatively affected area accounted for only 1.75%, scattered in the eastern part of the Lake District and northwest of Tianjun County (Fig. 6a [Figure 6: see original paper]). Areas subject to positive and negative effects of precipitation on NPP accounted for 67.60% and 32.40%, respectively, with a greater positive effect in Gangcha County and the southwest bank of the Lake District and a greater negative effect on the southeastern bank (Fig. 6b [Figure 6: see original paper]). Areas subjected to positive and negative effects of sunshine duration on NPP accounted for 78.81% and 21.19%, respectively, with a greater positive effect on the southern bank of the Lake District and a greater negative effect in

a strip-shaped pattern in the middle of Tianjun County and Gangcha County (Fig. 6c [Figure 6: see original paper]).

3.3 Relative Effects of Human Activities and Climate Change on Grassland NPP

The relative effects of climate change and human activities on grassland NPP were quantified using Equations 6–8 (Fig. 7 [Figure 7: see original paper]). Over the past 22 years, areas with positive effects of climate factors on grassland NPP reached 84.07%, significantly influenced by precipitation and sunshine duration. This positive effect was especially evident on the northern and southern shores of Qinghai Lake. In contrast, 15.93% of the area showed negative contributions, scattered across central Gangcha County, northwestern Tianjun County, and the eastern coast of Qinghai Lake, where the primary influencing factor was sunshine duration. Human activities also positively contributed to grassland NPP, with the area subject to positive contribution reaching 91.27% and showing larger contributions in the Buha River area on the northern and western banks of the Lake District. The area subject to negative contribution reached 8.73%, primarily located at the northern edge of the basin and along the southern and southeastern banks of the Lake District.

From 2001 to 2022, the grassland restoration area was about 19.2×10^3 km², constituting 98.47% of the grassland area. Grassland recovery due to climate change accounted for 7.71% and was predominantly distributed in the northern area of the research area and southern Qinghai Lake. In contrast, human activities contributed to 14.82% of the recovery, primarily found in central Gangcha County, northwestern Tianjun County, and along the eastern bank of the Lake District. The remaining grassland restoration area was co-dominated by these two factors, accounting for 75.93% of the total area. Grassland degradation, scattered around Qinghai Lake, represented only 1.53% of the area (Fig. 8 [Figure 8: see original paper]).

Climate change and human activities accounted for 35.00% and 65.00%, respectively, of grassland restoration. High-value areas influenced by climatic factors were predominantly distributed in southern Qinghai Lake and the northern edge of the basin (Fig. 9a [Figure 9: see original paper]), whereas areas shaped by human activities were found in the northern Lake District, including its western and eastern banks (Fig. 9b [Figure 9: see original paper]).

3.4 Assessment of Accuracy

We assessed the accuracy of spatial interpolation results for various meteorological factors using the indirect verification method. The correlation coefficients between the simulated and verified values of precipitation, temperature, and sunshine duration were 0.92, 0.83, and 0.94, respectively. These results indicated that simulated values of the three factors were highly correlated with verified values and that the correlation was significant ($P < 0.01$). Moreover,

the root mean square error (RMSE) between simulated and verified values of temperature, precipitation, and sunshine duration was 0.23°C, 19.41 mm, and 22.91 h, respectively. In summary, the overall accuracy of meteorological factor interpolation was high and suitable for analyzing watershed climate change (Fig. 10 [Figure 10: see original paper]).

We considered the actual grassland NPP from the CASA model as the validation value and compared it with that from the MOD17A3HGF model for accuracy validation. The results revealed that the correlation coefficient of NPP between MOD17A3HGF and CASA was 0.87, suggesting that the simulated and verified values had consistent change trends and that the correlation was significant ($P < 0.01$). The RMSE of NPP between MOD17A3HGF and CASA was relatively small at 10.040 g C/(m² · a) (Fig. 11 [Figure 11: see original paper]). In summary, it is feasible to study the productivity of the Qinghai Lake Basin using the MOD17A3HGF product.

4.1 Effect of Human Activities on Grassland NPP

Human activities generally affect the growth of alpine grasslands in two primary ways: on one hand, excessive reclamation and unreasonable urbanization have destroyed the ecological environment of vegetation; on the other hand, people have maintained the balance of grassland ecosystems and promoted grassland restoration and growth through rational grazing management, ecological engineering, and implementing protection measures. From 2001 to 2022, grassland NPP in the area increased, with only a few areas around the lake experiencing degradation. These findings coincide with results reported by Wu et al. (2023). The synergistic effect of climate and human factors has facilitated grassland rehabilitation in this area, as indicated by other studies (Xu et al., 2016; Chen et al., 2020; Tuoku et al., 2024). However, studies have revealed that human factors contribute substantially more (65.00%) to the increase in NPP than climatic factors (Dai et al., 2024; Long et al., 2024). From 2001 to 2019, the grasslands in the Qinghai Lake basin were in a state of mild overloading. Nonetheless, grazing pressure in the study area and its counties exhibited a downward trajectory over time, indicating an improvement trend (Fig. S1). Based on the “Protection and Comprehensive Management Plan of the Ecological Environment in the Qinghai Lake Basin,” we found that most grassland degradation control projects in Tianjun County were concentrated along the Buha River, which aligns with the high-value areas of grassland restoration driven by human activities (Table S1). In summary, several ecological projects from the “Western Development Strategy” have yielded remarkable results that have driven the restoration of grasslands in the Qinghai Lake Basin (Mu et al., 2013). This result also confirms the conclusion that the significant recovery of vegetation in northern China since 2000 was mainly due to well-executed ecological initiatives (Liu et al., 2022). Bao et al. (2018) also reported that the “Ecological Environment Protection Project” launched and implemented in 2008 was the key factor leading to a considerable increase in vegetation cover from 2008 to 2016 in the

Qinghai Lake Basin. The few degraded areas of grassland in the study area were scattered around the lake, which can be attributed to rising temperatures, changing precipitation patterns, overloading livestock, tourism activities, and other factors (Zhang et al., 2017; Li et al., 2019).

4.2 Effect of Climate Change on Grassland NPP

From 2001 to 2020, a significant warming trend was found across 79.00% of the Qinghai-Xizang Plateau, with annual precipitation increasing by 5.00 mm/a (Zhou et al., 2024). Our study revealed that meteorological conditions in the study area were generally marked by increasing temperature and precipitation (Figs. 5a and 5b [Figure 5: see original paper]). Geng et al. (2024) emphasized that the warming and moistening climate has increased the carbon sink capacity in the eastern Qinghai-Xizang Plateau. This result aligns with our findings, which suggest that climatic factors primarily contribute to grassland NPP. Grassland NPP in the area was positively influenced by temperature, precipitation, and solar radiation, with sunshine duration playing the most significant role. This conclusion aligns with that of Zhang et al. (2022), who found that solar radiation exerts a greater influence on grassland development than temperature and precipitation in northern China. The study of Ge et al. (2021) also revealed that radiation positively contributes to NPP in most areas of the country. Xu and Wang (2016) noted that grassland NPP is related primarily to temperature and solar radiation. Climate change contributed 35.00% to grassland restoration in the area, primarily affecting the southern Lake District and northern basin (Fig. 9a [Figure 9: see original paper]), with precipitation and sunshine duration being the primary factors. Climatic conditions inhibited NPP in the basin, affecting mainly central Gangcha County and northwestern Tianjun County (Fig. 7a [Figure 7: see original paper]). However, since the positive contributions of human interventions outweigh the detrimental effects of climatic factors in these areas, they further fostered the enhancement of grassland quality, resulting in increased grassland NPP.

4.3 Effects of Other Factors on Grassland NPP

Along with the meteorological factors previously discussed, grassland NPP is also influenced by many other environmental factors, including terrain, CO₂ concentration, nitrogen deposition, and soil characteristics (Wang et al., 2022b; She et al., 2024). We found that atmospheric CO₂ concentration in the Qinghai Lake Basin continued to increase from 2001 to 2020, and its correlation coefficient with grassland NPP reached 0.67 ($P < 0.01$) (Fig. S2). This result can be attributed to the fact that an increase in CO₂ concentration can enhance photosynthesis in grassland vegetation, which in turn promotes the accumulation of organic matter in plants (Zhao et al., 2024). Nitrogen deposition has the greatest effect on grassland vegetation productivity, along with climate change and increasing atmospheric CO₂ concentrations. Wang et al. (2024b) found that nitrogen deposition significantly increased the NPP of grassland ecosystems but

with a critical nitrogen load. Edaphic parameters, such as soil texture, structure, and organic matter content, as well as biological properties (soil microorganisms and soil animals), also have important effects on grassland ecosystem succession (Li et al., 2024). Liu (2022) found that in the semi-arid area of the Qilian Mountains, grassland NPP is strongly and positively associated with the water content and organic carbon content of the soil in the 0-30 cm layer. Wu et al. (2013) found that soil nutrient content directly affects the productivity of different grassland communities. Moreover, we analyzed the effect of grazing pressure and ecological engineering management points on grassland NPP, but human activities such as urbanization, railways, and tourism were not considered. Therefore, researchers need to focus on analyzing the relationships among environment, human interventions, and other indicators of grassland NPP to seek more comprehensive and reasonable results in future studies.

5 Conclusions

In this study, we first explored the spatiotemporal patterns of grassland productivity in the Qinghai Lake Basin using the MOD17A3 NPP product. Then, we quantified the relative effects of different drivers on NPP variations by combining partial derivatives with the residual method of physiological and ecological processes. Additionally, we assessed the effects of climate change and human activities on the dynamics of grassland NPP. The main conclusions are as follows:

1. Grassland NPP progressively decreased from the Lake District toward the northwestern area and significantly increased from 2001 to 2022.
2. Over the past 22 years, climatic conditions of the area have shifted toward humidity and warmth, marked by an increase rate of $0.02^{\circ}\text{C}/\text{a}$ in temperature and $1.80\text{ mm}/\text{a}$ in precipitation, whereas sunshine duration decreased at a rate of $0.70\text{ h}/\text{a}$. Climatic factors had a positive effect on NPP, with sunshine duration having the greatest relative contribution among these factors.
3. About 98.47% of the grasslands in the Qinghai Lake Basin experienced recovery over the past 22 years, which was promoted mainly by climate factors and human activities. Human activities significantly enhanced grassland restoration via ecological restoration projects, with a relative contribution as high as 65.00%, whereas climatic factors contributed 35.00%, which was relatively weak.

These results not only provide important scientific support for ecological restoration and sustainable development of the basin but also offer new ideas for research on similar ecologically fragile areas.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was financially supported by the Lanzhou Youth Science and Technology Talent Innovation Project (2023-QN-2), the Gansu Haizhi Plan Project (GSHZJH 12-2025-04), the National Key Research and Development Program of China (2019YFC0507404), and the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA20100101).

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Appendix

Fig. S1 Spatiotemporal variation of the livestock pressure index in the Qinghai Lake Basin (a) and livestock pressure index in different areas (b) from 2001 to 2019

Table S1 Degraded grassland control projects in Tianjun County

Implementation Township	Implementation Project	Implementation Year
Jianghe Town	Control of weeds and poisonous plants on degraded grassland	2009, 2010
	Control of grasshopper on degraded grassland	
	Desertification-type degraded grassland control	
	Control of caterpillar on degraded grassland	
Kuaierma Town	Control of weeds and poisonous plants on degraded grassland	2009, 2010
	Control of grasshopper on degraded grassland	
	Control of grasshopper on degraded grassland	

Implementation Township	Implementation Project	Implementation Year
Shengge Town	Desertification-based degraded grassland control	2009, 2010
	“Black soil beach” type degraded grassland control	
Xinyuan Town	Desertification-based degraded grassland control	2009, 2010
	“Black soil beach” type degraded grassland control	
Zhihema Town	Control of weeds and poisonous plants on degraded grassland	2009, 2010
	Control of caterpillar on degraded grassland	
	Desertification-based degraded grassland control	
	Control of weeds and poisonous plants on degraded grassland	
Zhihema Town	Control of grasshopper on degraded grassland	2009, 2010
	Desertification-based degraded grassland control	
	Control of weeds and poisonous plants on degraded grassland	

Fig. S2 Relationship between CO₂ concentration and grassland net primary productivity (NPP)

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

Source: ChinaXiv – Machine translation. Verify with original.