Spatial and temporal change patterns of net primary productivity and its response to climate change in the Qinghai–Tibet Plateau of China from 2000 to 2015 postprint

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Abstract

The vegetation ecosystem of the Qinghai–Tibet Plateau in China, considered to be the ′′natural laboratory′′ of climate change in the world, has undergone profound changes under the stress of global change. Herein, we analyzed and discussed the spatial-temporal change patterns and the driving mechanisms of net primary productivity (NPP) in the Qinghai–Tibet Plateau from 2000 to 2015 based on the gravity center and correlation coefficient models. Subsequently, we quantitatively distinguished the relative effects of climate change (such as precipitation, temperature and evapotranspiration) and human activities (such as grazing and ecological construction) on the NPP changes using scenario analysis and Miami model based on the MOD17A3 and meteorological data. The average annual NPP in the Qinghai–Tibet Plateau showed a decreasing trend from the southeast to the northwest during 2000–2015. With respect to the interannual changes, the average annual NPP exhibited a fluctuating upward trend from 2000 to 2015, with a steep increase observed in 2005 and a high fluctuation observed from 2005 to 2015. In the Qinghai–Tibet Plateau, the regions with the increase in NPP (change rate higher than 10%) were mainly concentrated in the Three-River Source Region, the northern Hengduan Mountains, the middle and lower reaches of the Yarlung Zangbo River, and the eastern parts of the North Tibet Plateau, whereas the regions with the decrease in NPP (change rate lower than −10%) were mainly concentrated in the upper reaches of the Yarlung Zangbo River and the Ali Plateau. The gravity center of NPP in the Qinghai–Tibet Plateau has moved southwestward during 2000–2015, indicating that the increment and growth rate of NPP in the southwestern part is greater than those of NPP in the northeastern part. Further, a significant correlation was observed between NPP and climate factors in the Qinghai–Tibet Plateau. The regions exhibiting a significant correlation between NPP and precipitation were mainly located in the central and eastern Qinghai–Tibet Plateau, and the regions exhibiting a significant correlation between NPP and temperature were mainly located in the southern and eastern Qinghai–Tibet Plateau. Furthermore, the relative effects of climate change and human activities on the NPP changes in the Qinghai–Tibet Plateau exhibited significant spatial differences in three types of zones, i.e., the climate change-dominant zone, the human activity-dominant zone, and the climate change and human activity interaction zone. These research results can provide theoretical and methodological supports to reveal the driving mechanisms of the regional ecosystems to the global change in the Qinghai–Tibet Plateau.

Full Text

Preamble

Spatial and temporal change patterns of net primary productivity and its response to climate change in the Qinghai–Tibet Plateau of China from 2000 to 2015

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Abstract: The vegetation ecosystem of the Qinghai–Tibet Plateau in China, considered a "natural laboratory" of global climate change, has undergone profound changes in response to global change. We analyzed the spatiotemporal patterns and driving mechanisms of net primary productivity (NPP) on the Qinghai–Tibet Plateau from 2000 to 2015 using gravity center and correlation coefficient models. We then quantitatively distinguished the relative effects of climate change (precipitation, temperature, and evapotranspiration) and human activities (grazing and ecological construction) on NPP changes through scenario analysis and the Miami model based on MOD17A3 and meteorological data.

The average annual NPP showed a decreasing trend from southeast to northwest during 2000–2015. Inter-annually, average annual NPP exhibited a fluctuating upward trend, with a steep increase in 2005 and high fluctuations from 2005 to 2015. Regions with NPP increase (change rate $> 10\%$) were concentrated in the Three-River Source Region, northern Hengduan Mountains, middle and lower reaches of the Yarlung Zangbo River, and eastern North Tibet Plateau, while regions with NPP decrease (change rate $< -10\%$) were mainly in the upper reaches of the Yarlung Zangbo River and the Ali Plateau.

The gravity center of NPP moved southwestward during 2000–2015, indicating that NPP increment and growth rate were greater in the southwestern than northeastern parts. Significant correlations existed between NPP and climate factors across the plateau. Regions with significant NPP-precipitation correlations were located mainly in central and eastern areas, while significant NPP-temperature correlations occurred primarily in southern and eastern regions. The relative effects of climate change and human activities on NPP changes showed distinct spatial patterns across three zones: climate change-dominant, human activity-dominant, and interaction zones. These results provide theoretical and methodological support for revealing ecosystem response mechanisms to global change in the Qinghai–Tibet Plateau.

Keywords: NPP; gravity center model; driving mechanisms; global change; human activities; Qinghai–Tibet Plateau

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1 Introduction

Net primary productivity (NPP) represents the amount of organic dry matter accumulated by green plants per unit time and area [**?**, **?**, **?**]. As the residual organic matter after photosynthetic production minus autotrophic respiration, NPP constitutes a core component of carbon budget and climate change research, serving as an important indicator for assessing ecosystem health and sustainable development [**?**, **?**, **?**]. Analyzing spatiotemporal patterns and driving mechanisms of NPP in regional vegetation ecosystems is significant for understanding ecosystem responses to climate change and provides a scientific basis for ecological protection, yield estimation, resource exploitation, natural resource management, and socioeconomic development strategies [**?**].

NPP research internationally employs climate models (e.g., BIOME-BioGeoChemical Cycle (BIOME-BGC), Carnegie-Ames-Stanford Approach (CASA), and Global Production Efficiency (GLO-PEM)) and remote sensing technology, while domestic scholars have applied empirical models (e.g., Ball–Berry and Boreal Ecosystem Productivity Simulator (BEPS)) to study NPP across various spatial scales in China, including northwest, northeast, and southwest regions [?, ?, ?, ?, ?, ?].

Driving mechanisms of NPP responses to climate change vary due to differences in data sources, study areas, and spatiotemporal scales [?, ?]. Although global NPP increased from 1980 to 2000, the underlying causes differed regionally [?, ?]. Under global change, China's climate has shifted significantly, with terrestrial vegetation NPP showing an increasing trend [?, ?, ?, ?]. While climate change reduces hydrothermal constraints on vegetation growth, NPP responses exhibit obvious regional differences [?, ?, ?, ?, ?], necessitating further investigation into driving mechanisms across different regions [?].

The Qinghai–Tibet Plateau's unique geography, altitude, climate, and geomorphology create diverse climatic and ecosystem types. This special geographic unit plays a crucial role in regulating and indicating global change, serving as a "natural laboratory" for climate change studies worldwide [?, ?, ?, ?]. Although previous studies have investigated NPP change patterns using conventional methods (e.g., correlation analysis), relationships between NPP and climate factors and the relative effects of climate change versus human activities remain unclear [?, ?, ?, ?].

The "gravity center" concept, derived from physics, indicates the point where gravitational forces on an object exert a resultant force [?]. In geography, this concept has been extensively applied to population, economy, food, land use, ecological environment, and regional development studies [?]. Spatial variation in the gravity center effectively reflects the degree and trend of geographical phenomena.

This study introduces a gravity center model to analyze spatiotemporal patterns and driving mechanisms of NPP in the Qinghai–Tibet Plateau from 2000 to 2015, combined with conventional analytical methods. We also quantitatively distinguished the relative effects of climate change and human activities on NPP changes, providing data and theoretical support for revealing ecosystem evolution patterns and response mechanisms to global change in this region.

2.1 Study Area

The Qinghai–Tibet Plateau extends from the Pamir Plateau and Karakorum Mountains in the west to the Hengduan Mountains in the east, and from the Himalaya Mountains in the south to the Kunlun, Altun, and Qilian Mountains in the north ($26^\circ 00' 12''$–$39^\circ 46' 50''$N, $73^\circ 18' 52''$–$104^\circ 46' 59''$E). The plateau covers approximately 2.5×10^7 km^2 with an average altitude exceeding 4000 m, earning it the name "the third pole." The annual mean temperature is below 0°C in the hinterland and decreases with altitude and latitude. Mean annual precipitation declines from 2000 mm in the southeast to 50 mm in the hinterland [?].

In summer, abundant precipitation occurs in most southeastern plateau regions due to monsoon influence and humid airflow from the southwest Indian Ocean. In winter, strong winds (lasting up to 200 days in some areas) and scarce precipitation prevail due to dry westerlies. Complex and diverse vegetation types—including forests, meadows, grasslands, and deserts—appear successively across the plateau's horizontal belt spectrum, with climate gradually transitioning from maritime wet conditions in the southeast to continental arid conditions in the hinterland [**?**].

2.2 Data Sources

NPP data for 2000–2015 were obtained from the MOD17A3 dataset (https://lpdaac.usgs.gov/) with 1 km spatial and 1-year temporal resolutions. Daily precipitation and mean daily temperature data from 229 meteorological stations across the Qinghai–Tibet Plateau and surrounding areas were obtained from the China Meteorological Data Network (http://data.cma.cn/). MOD17A3 data were mosaicked and reprojected using the MODIS Projection Tool. Annual mean temperature and precipitation were interpolated to 1 km × 1 km grids using the Cokriging method in ArcGIS 10.3. To address uneven spatial distribution of meteorological stations in the western plateau, we supplemented station data using the China Meteorological Forcing Dataset (http://westdc.westgis.ac.cn), particularly for central and western regions. Station locations are shown in Figure 1 [Figure 1: see original paper].

3.1 Change Trend Analysis

Linear regression analysis can eliminate influences of extreme climate in specific years [**?**]. This study adopted linear regression to analyze NPP time series trends, calculated as:

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

where θ_{slope} denotes the gradient of vegetation NPP change trend; n is the number of years (16); i is the time variable ($i = 1, 2, 3, \ldots, 16$); and NPP_i is NPP in the ith year. The NPP change rate is:

$$NPP_{cr} = \frac{\theta_{slope} \times n}{NPP_{mean}} \times 100\%$$

where NPP_{cr} is the NPP change rate (%); NPP_{mean} is the average annual NPP during 2000–2015; and n is the number of years.

3.2 Correlation Analysis

Correlation analysis indicates the degree and direction of relationships between variables [**?**, **?**, **?**, **?**]. This study analyzed correlations and significance levels between NPP and climate factors (temperature and precipitation) using Pearson's correlation coefficient at confidence levels of 0.05 and 0.01. The correlation coefficient, partial correlation coefficient, and complex correlation coefficient were calculated as Equations 3–5, respectively:

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

where $r_{x,y}$ is the correlation coefficient between variables x and y; x_i and y_i denote values of variables x and y in the ith year; and $\bar{x}$ and $\bar{y}$ denote average values. The r value ranges from –1 to 1, with values > 0 indicating positive correlation and < 0 indicating negative correlation.

In Equations 4 and 5, $r_{xy1,y2}$ refers to the partial correlation coefficient of x and $y1$ after fixing $y2$; $r_{x,y1}$ is the correlation coefficient between x and $y1$; $r_{x,y2}$ between x and $y2$; $r_{y1,y2}$ between $y1$ and $y2$; $R_{x,y1y2}$ is the complex correlation coefficient among x, $y1$, and $y2$; and $r_{xy2,y1}$ is the partial correlation coefficient between x and $y2$ after fixing $y1$. T-tests and F-tests assessed significance of partial and complex correlation coefficients:

$$T = r_{xy1,y2} \times \sqrt{\frac{n - m - 1}{1 - r_{xy1,y2}^2}}$$

$$F = \frac{R_{x,y1y2}^2/m}{(1 - R_{x,y1y2}^2)/(n - m - 1)}$$

where n is the number of samples and m is the number of variables.

3.3 Gravity Center Model

In a gravity center model, z_i represents the attribute value of the ith plane space unit (grid) [?]. When the Cartesian coordinate is (x_i, y_i), the spatial mean of the region comprising n plane space units is defined as Cartesian coordinate point $(\bar{x}, \bar{y})$:

$$\bar{x} = \frac{\sum_{i=1}^{n} z_i x_i}{\sum_{i=1}^{n} z_i}$$

$$\bar{y} = \frac{\sum_{i=1}^{n} z_i y_i}{\sum_{i=1}^{n} z_i}$$

For spatial phenomena, an unbalanced distribution or "deviation of the gravity center" occurs when the regional gravity center significantly differs from the geometric center. The deviation direction points toward the "high-density" area, and deviation distance describes the degree of unbalanced distribution. The migration trajectory of the gravity center across different periods reflects the evolution of spatial distribution. Formulas for migration direction and distance are:

$$\theta = \arctan\left(\frac{y_{t+m} - y_t}{x_{t+m} - x_t}\right)$$

$$d_m = \sqrt{(x_{t+m} - x_t)^2 + (y_{t+m} - y_t)^2}$$

where θ and d_m are the migration direction and distance; y_{t+m} and y_t are latitude coordinates at times $t+m$ and t; and x_{t+m} and x_t are longitude coordinates at times $t+m$ and t.

3.4 Miami Model

This study adopted the Miami model to estimate potential vegetation NPP. Based on Liebig's law of the minimum, this was the first NPP estimation model and has been widely applied. It includes functions of annual mean temperature and precipitation [?]:

$$NPP_{climate} = \min\begin{cases} 3000 \times (1 + \exp(1.315 - 0.119 \times T))^{-1} \\ 3000 \times (1 - \exp(-0.000664 \times P)) \end{cases}$$

where $NPP_{climate}$ is potential vegetation NPP; T is annual mean temperature ($^{\circ}$C); and P is annual precipitation (mm).

3.5 Method for Distinguishing Relative Effects of Climate Change and Human Activities

Climate change and human activities are the main factors affecting vegetation NPP dynamics. Following Mao et al. (2015), we quantitatively evaluated their relative effects. Three NPP types were identified: (1) actual NPP (NPP_{actual}) from MOD17A3, representing combined climate and human effects; (2) potential NPP ($NPP_{climate}$) from the Miami model, representing climate effects only; and (3) human activity-related NPP (NPP_{human}) as the residual between $NPP_{climate}$ and NPP_{actual}, attributed to activities like grazing and ecological construction.

We calculated change trends of $NPP_{climate}$ and NPP_{human} (K_c and K_h) to assess their relative effects. Positive K_c indicates climate change promotes vegetation restoration, while negative K_c indicates climate-induced degradation. Positive K_h indicates human activities cause degradation, while negative K_h

indicates human-induced restoration. The change trend of NPP_{actual} (K_a) indicates overall vegetation restoration (positive) or degradation (negative). Table 1 defines six possible scenarios for NPP changes [?, ?].

Table 1 Relative effects of climate change and human activities on NPP changes

Scenario	K_a (Actual NPP)	K_c (Climate)	K_h (Human)	Interpretation
1	+	+	-	Restoration, climate dominant
2	+	-	+	Restoration, human activity dominant
3	+	+	+	Restoration, combined effects
4	-	-	+	Degradation, climate dominant
5	-	+	-	Degradation, human activity dominant
6	-	-	-	Degradation, combined effects

Note: K_a refers to the change trend of actual NPP (NPP_{actual}); K_c and K_h refer to change trends of potential NPP ($NPP_{climate}$) and human activity-related NPP (NPP_{human}), respectively.

4.1.1 Spatial Distribution Patterns of Average Annual NPP

Figure 2 [Figure 2: see original paper] shows that average annual NPP distribution differed significantly across the Qinghai–Tibet Plateau during 2000–2015, generally decreasing from southeast to northwest in relation to regional hydrothermal conditions. The plateau-wide average annual NPP was 167.52 g $C/(m^2 \cdot a)$. Most areas—including the North Tibet Plateau, middle and upper Yarlung Zangbo River reaches, and Ali Plateau—had average annual NPP below 400.00 g $C/(m^2 \cdot a)$. A high-value zone occurred in the southeastern plateau, with NPP $>$ 600.00 g $C/(m^2 \cdot a)$ mainly in the southern Hengduan Mountains. Areas with 200.00–400.00 g $C/(m^2 \cdot a)$ NPP were distributed in the West Sichuan Plateau. The Hengduan Mountains showed decreasing NPP from south to north and west to east, with high values concentrated in the southern part due to vegetation type, topography, and climate.

4.1.2 Spatial Change Patterns of Average Annual NPP

During 2000–2015, regions with NPP change rates of 10%–30% were most extensive, covering 45.55% of the study area, followed by stable regions (–10% to 10%) at 33.39% (Fig. 3 [Figure 3: see original paper]). Regions with NPP reduction ($< -30\%$) were smallest (0.91%). These results indicate an overall increasing inter-annual NPP trend, with stable ($-10\% <$ change rate $< 10\%$) and increasing (change rate $> 10\%$) regions comprising 94.20% of the study area.

Stable regions (–10% to 10% change rate) were mainly distributed in the eastern and southern plateau, including the northern Hengduan Mountains and southern Ali Plateau (Fig. 4 [Figure 4: see original paper]). Regions with $> 30\%$ NPP increase occurred in the eastern North Tibet Plateau, lower Yarlung Zangbo River reaches, and middle Hengduan Mountains. Regions with 10%–30% NPP increase were most widespread, concentrated in the Three-River Source Region, northern Hengduan Mountains, middle and lower Yarlung Zangbo River reaches, and middle and eastern North Tibet Plateau. NPP reduction areas (change rate $< -10\%$) were mainly in the upper Yarlung Zangbo River reaches and Ali Plateau.

The gravity center effectively represents spatial imbalance and bias in NPP changes. We calculated annual NPP gravity centers and the average for the entire study period (16 years) (Fig. 5 [Figure 5: see original paper]). Gravity centers concentrated in the southeastern plateau, indicating larger total NPP there than in the northwestern part, consistent with the southeast-to-northwest decreasing trend shown in Figure 2.

Using the mean NPP gravity center (2000–2015) as the origin, we established a polar coordinate system to analyze spatial distribution patterns. The number and percentage of NPP gravity centers in different quadrants were estimated. Results showed 37.50% of gravity centers in the southwest quadrant, followed by 25.00% in the northeast quadrant, indicating relatively large NPP increments and growth rates in these regions. Together, these quadrants accounted for 62.50% of all gravity centers.

The northwest and southeast quadrants each contained 18.75% of gravity centers. Dividing the area by coordinate axes, the northern half had slightly fewer gravity centers (43.75%) than the southern half (56.25%), indicating larger NPP increments and growth rates in the southern plateau during 2000–2015. Gravity centers showed larger migration distances from the origin in 2002, 2003, 2005, and 2014, indicating significant NPP increases in northeastern and southwestern parts. In 2006, 2007, and 2008, migration distances were smaller, implying relatively consistent NPP changes across plateau regions.

We analyzed NPP gravity center migration directions at different temporal scales (3, 5, and 16 years) to explore spatial variations (Fig. 7 [Figure 7: see original paper]). From 2000–2002 to 2003–2005, the gravity center moved eastward, indicating higher NPP increments and growth rates in the eastern than western parts. From 2003–2005 to 2006–2008, it shifted southwestward, showing greater NPP growth in the southwestern than northeastern parts. Compared with 2006–2008, gravity centers during 2009–2011 and 2012–2015 moved westward, suggesting larger NPP increments in the western plateau during 2009–2015.

On a 5-year scale, the gravity center first moved southeastward from 2000–2004 to 2005–2009, then westward from 2005–2009 to 2010–2015. Thus, NPP increments were greater in the southeastern part during 2005–2009 and in the western part during 2010–2015. Overall, the NPP gravity center moved southwestward during 2000–2015, indicating larger NPP increments and growth rates in the southwestern than northeastern parts.

4.2 Inter-Annual Variations of Average Annual NPP

From 2000 to 2015, average annual NPP showed an increasing trend with slight fluctuations (Fig. 8 [Figure 8: see original paper]), ranging 0.00–32.88 g C/($m^2 \cdot$ a). The maximum NPP was 182.95 g C/($m^2 \cdot$ a) in 2013, followed by 180.88 g C/($m^2 \cdot$ a) in 2000. Before 2005, average annual NPP was below 160.00 g C/($m^2 \cdot$ a) with minimal increase. After 2005, NPP increased significantly, averaging 170.00 g C/($m^2 \cdot$ a). Notable peaks occurred in 2006 and 2013 (180.88 and 182.95 g C/($m^2 \cdot$ a), respectively). This increasing trend resulted primarily from ecological projects implementing "returning farmland to grassland" and "returning grazing land to grassland."

4.3.1 Changes of Climate Factors during 2000–2015

Annual precipitation ranged from 379.36 to 541.10 mm, averaging 490.65 mm, with maximum in 2010 and minimum in 2007 (Fig. 9 [Figure 9: see original paper]). A slight decreasing trend occurred during the study period, with spatial distribution decreasing from southeast to northwest. Annual mean temperature increased significantly, ranging from 0.67°C (2002) to 2.98°C (2007), with a study period average of 1.48°C.

4.3.2 Correlation Analyses of NPP with Precipitation and Temperature

Because precipitation and temperature influences on NPP are often interacting and dependent, we calculated partial and complex correlation coefficients between NPP and these climate factors pixel by pixel (Fig. 10 [Figure 10: see original paper]).

Partial correlation coefficients between NPP and annual precipitation ranged from –0.86 to 0.91. Positive correlations covered 54.57% of the study area, mainly in central and northeastern plateau regions. Negative correlations were concentrated in the southern North Tibet Plateau, upper Yarlung Zangbo River Basin, and Ali Plateau.

Partial correlation coefficients between NPP and temperature were positive in 47.13% of the study area, mainly in eastern and southern plateau regions. Negative correlations accounted for 52.87%, primarily in the western Three-River Source Region, upper Yarlung Zangbo River Basin, southern Hengduan Mountains, and surrounding areas.

Significance was evaluated using T-tests. For NPP-precipitation partial correlations, 15.83% of the study area passed the T-test at $P < 0.05$, and 5.34% at $P < 0.01$. Extremely significant NPP-precipitation correlations were mainly in the western and eastern Three-River Source Region. For NPP-temperature partial correlations, approximately 12.65% passed at $P < 0.05$ and 6.13% at $P < 0.01$, with extremely significant correlations mainly in the lower Yarlung Zangbo River Basin.

Complex correlation coefficients between NPP and combined climate factors ranged from 0.00 to 0.94 (Fig. 10e). In F-test significance evaluation (Fig. 10f), approximately 16.32% of the area passed at $P < 0.05$ and 5.89% at $P < 0.01$. Extremely significant complex correlations were mainly in the middle and western Three-River Source Region, upper and lower Yarlung Zangbo River Basin, and West Sichuan Plateau.

4.4 Effects of Climate Change and Human Activities on NPP Changes

Vegetation restoration (NPP increase) occurred in 84.54% of the Qinghai–Tibet Plateau during 2000–2015, while degradation (NPP decrease) occupied 15.46% (Fig. 11 [Figure 11: see original paper]). Climate change-driven restoration accounted for 46.01% of the study area, mainly in western and central North Tibet Plateau and the Three-River Source Region. Human activity-driven restoration accounted for 34.33%, concentrated in the middle and lower Yarlung Zangbo River Basin and Hengduan Mountains. Combined climate and human effects caused restoration in 3.81% of the area, mainly in the southern Three-River Source Region.

Climate change-driven degradation occurred in 5.05% of the study area, discontinuously distributed in the upper Yarlung Zangbo River Basin and northern Hengduan Mountains. Human activity-driven degradation accounted for 10.20%, mainly in the Ali Plateau. Degradation from combined effects was distributed in the northern Yarlung Zangbo River Basin margin.

Thus, climate change dominated in A1 and A2 regions (climate change-dominant zone), the interaction zone (B) was considerably influenced by combined effects, and C1 and C2 regions (human activity-dominant zone) were dominated by human activities.

5.1 Spatial and Temporal Distribution Patterns of NPP

NPP spatial distribution decreased from southeast to northwest during 2000–2015, primarily reflecting precipitation and temperature patterns. Influenced by the South Asian monsoon, the southeastern Hengduan Mountains receive abundant precipitation and support diverse vegetation types (broad-leaved forests, coniferous forests, shrubs) with high NPP. The lower Yarlung Zangbo River reaches, affected by warm, moist Indian Ocean airflow, have high forest cover and NPP in rainforests, monsoon forests, and broad-leaved forests.

Most northern Tibet Plateau areas have relatively low NPP due to high altitude, low temperature, low precipitation, and vegetation types dominated by grasslands, alpine meadows, and sparse shrubs [**?**]. Deserts and desert grasslands with the lowest NPP are widespread in the Ali Plateau due to scarce precipitation and low temperatures. Average annual NPP showed an upward trend during 2000–2004, then a steep increase after 2004, reflecting considerable forest and grassland restoration following "returning farmland to grassland" and "returning grazing land to grassland" projects. NPP increased sharply in 2005, with high fluctuations during 2005–2015.

5.2 Effects of Climate Factors on NPP

Our analysis indicates that NPP-climate factor correlations vary significantly across regions, likely related to altitude, climate type, and vegetation. In central, northeastern, and western plateau regions above 4000 m altitude with low precipitation, NPP was positively correlated with precipitation, which became the dominant factor restricting vegetation growth. Grasslands and alpine meadows in these regions showed high precipitation sensitivity [?].

Conversely, NPP was negatively correlated with precipitation in the southeastern Hengduan Mountains and middle-lower Yarlung Zangbo River Basin. Precipitation was abundant and not limiting, but high rainfall erosivity, steep slopes, and severe soil erosion (freeze-thaw and hydraulic) occurred. Negative NPP-precipitation correlations in some regions (especially Hengduan Mountains) were also associated with reduced solar radiation during increased precipitation [?], damaging vegetation ecosystems.

Positive NPP-temperature correlations occurred mainly in southern Tibet Plateau and northern Hengduan Mountains, where high altitude, abundant precipitation, and low temperature (limiting vegetation growth) meant higher temperatures enhanced photosynthesis. Negative correlations were concentrated in central and northern plateau regions with scarce precipitation, where temperature increases exacerbated drought despite promoting photosynthesis, inhibiting vegetation growth.

5.3 Relative Effects of Climate Change and Human Activities on NPP Changes

Climate change and human activities were the primary drivers of NPP changes in the Qinghai–Tibet Plateau. Using NPP_{actual} (MOD17A3) and $NPP_{climate}$ (Miami model), we established comparable indicators to unify climate and human effects on vegetation degradation or restoration. Results showed significant spatial differences in their relative effects, dividing the plateau into three zones: climate change-dominant, human activity-dominant, and interaction zones.

The climate change-dominant zone comprises A1 (climate-induced NPP increase) and A2 (climate-induced NPP decrease). Figure 12 [Figure 12: see original paper] shows spatial distributions of precipitation and temperature trend coefficients. In A1, increasing precipitation and temperature enhanced vegetation photosynthesis and growth [?]. In A2, temperature increases combined with scarce precipitation caused drought, degrading vegetation ecosystems.

The human activity-dominant zone comprises C1 (human-induced NPP decrease) and C2 (human-induced NPP increase). Grazing and farming dominated these regions, but ecological projects ("returning farmland to grassland" and "returning grazing land to grassland") created divergent effects. Overgrazing and reclamation dominated C1, while ecological protection policies were essential in C2 [**?**]. The interaction zone (B) represents a transitional area where human effects weaken and climate effects strengthen. Thus, significant spatiotemporal differences characterize the relative effects of climate change and human activities on NPP changes.

6 Conclusions

This study examined spatiotemporal patterns and driving mechanisms of NPP in the Qinghai–Tibet Plateau during 2000–2015. Average annual NPP decreased from southeast to northwest. Inter-annually, NPP showed a fluctuating upward trend, with a steep rise in 2005 and high fluctuations during 2005–2015. NPP increments and growth rates were greater in the southwestern than northeastern parts. Significant NPP-precipitation correlations occurred mainly in central and eastern regions, while significant NPP-temperature correlations appeared in southern and eastern areas. The relative effects of climate change and human activities on NPP changes showed distinct spatial patterns across three zones: climate change-dominant, human activity-dominant, and interaction zones.

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