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Identifying the Relative Contributions of Climate and Grazing to Both Direction and Magnitude of Alpine Grassland Productivity Dynamics from 1993 to 2011 on the Northern Tibetan Plateau

Yunfei Feng [1], Jianshuang Wu [1,2,*], Jing Zhang [3], Xianzhou Zhang [1] and Chunqiao Song [4]

[1] Lhasa Plateau Ecosystem Research Station, Key Laboratory of Ecosystem Network Observation and Modelling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; fengyf.13b@igsnrr.ac.cn (Y.F.); zhangxz@igsnrr.ac.cn (X.Z.)

[2] Biodiversity—Ecological Modelling, Dahlem Center of Plant Science, Free University of Berlin, 14195 Berlin, Germany

[3] College of Global Change and Earth System Sciences, Beijing Normal University, Beijing 100875, China; jingzhang@bnu.edu.cn

[4] Department of Geography, University of California, Los Angeles, CA 90095, USA; chunqiao@ucla.edu

* Correspondence: wujs07s@zedat.fu-berlin.de or wujs.07s@igsnrr.ac.cn; Tel.: +86-10-6488-8176

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Abstract: Alpine grasslands on the Tibetan Plateau are claimed to be sensitive and vulnerable to climate change and human disturbance. The mechanism, direction and magnitude of climatic and anthropogenic influences on net primary productivity (NPP) of various alpine pastures remain under debate. Here, we simulated the potential productivity (with only climate variables being considered as drivers; NPP_P) and actual productivity (based on remote sensing dataset including both climate and anthropogenic drivers; NPP_A) from 1993 to 2011. We denoted the difference between NPP_P and NPP_A as NPP_{pc} to quantify how much forage can be potentially consumed by livestock. The actually consumed productivity (NPP_{ac}) by livestock were estimated based on meat production and daily forage consumption per standardized sheep unit. We hypothesized that the gap between NPP_{pc} and NPP_{ac} (NPP_{gap}) indicates the direction of vegetation dynamics, restoration or degradation. Our results show that growing season precipitation rather than temperature significantly relates with NPP_{gap}, although warming was significant for the entire study region while precipitation only significantly increased in the northeastern places. On the Northern Tibetan Plateau, 69.05% of available alpine pastures showed a restoration trend with positive NPP_{gap}, and for 58.74% of alpine pastures, stocking rate is suggested to increase in the future because of the positive mean NPP_{gap} and its increasing trend. This study provides a potential framework for regionally regulating grazing management with aims to restore the degraded pastures and sustainable management of the healthy pastures on the Tibetan Plateau.

Keywords: alpine grassland conservation; anthropogenic disturbance; ecological policies; climate change; grazing exclusion; grazing management; regional sustainability

1. Introduction

Grassland degradation is one of the most important issues closely related to biodiversity conservation, ecological functionality and sustainable development in a rapidly changing world [1–3]. Alpine pasture degradation on the Tibetan Plateau is mainly attributed to overgrazing under the ongoing climate change in the last decades [4]. Grassland degradation on this plateau has been increasingly claimed to not only threaten the livelihood and culture of local residents, but also to widely affect water security in East China and South Asia [5–7]. However, the mechanism, the direction and the magnitude of the relative influences of climatic and anthropogenic drivers are still unknown and under debate, especially in regard to the policy-making at a broader geospatial scale [8–10].

Climate change is believed to primarily impact functions and services of various ecosystems on the Tibetan Plateau. Total precipitation during the plant growing season (GSP) controls both temporal and spatial variabilities in vegetation phenology [9] and biomass production [11] in the context of global warming. Compared with fenced pastures, aboveground biomass and vegetation coverage are reduced by livestock grazing [12,13], so overgrazing by unfenced livestock is very likely to be the most important anthropogenic driver for pasture degradation on this plateau [4]. Furthermore, grazing exclusion with fencing is assumed to be a necessary trajectory for pasture restoration in the heavily degraded grasslands. However, the reduction in aboveground biomass reported in field surveys does not mean a decline in net primary productivity (NPP) because the proportion consumed by large herbivores is unknown. According to the intermediate disturbance hypothesis [14,15], a reasonable stocking rate might be better for maintaining stability in community structure and ecosystem functionality. Therefore, identifying the direction of vegetation dynamics, restoration or degradation, is the keystone of policy-making for alpine pasture conservation [16].

The direct and indirect impacts of either climate change or grazing management, especially on the potential and actual capacity of livestock, are still not clear. It is not necessary for vegetation to linearly respond to either climate change or grazing disturbance [17–19]. Therefore, disentangling and assessing their relative contributions to grassland degradation or restoration is still a challenge but increasingly required [8,20]. In addition, the difference between potential net primary productivity (NPP_P) and actual net primary productivity (NPP_A) [8,20] should be regarded as the proportion of grassland productivity that can be potentially consumed by livestock (NPP_{pc}) rather than the proportion of grassland productivity that has been actually consumed by livestock (NPP_{ac}) (Table 1). This is because NPP_A includes the plant's regrowth after grazing in the same season. In a recent study, Pan et al. [21] proposed a modified framework for assessing the relative impacts of climate and grazing on vegetation productivity at local small villages, and reported a method for estimating the actually consumed productivity by livestock (NPP_{ac}). At a coarser spatial scale, the field investigations generally cost more time and money, while remote sensing provides a more economical and effective data source for assessing historical vegetation dynamics.

To assist regionally specific policy-making concerning livestock regulation and pasture conservation in the future, we hypothesized that the NPP_{gap} (defined as $NPP_{pc} - NPP_{ac}$, Table 1) can effectively indicate the direction of grassland change over a defined period, a positive trend for restoration while a negative one for degradation. Using time-series tendency and correlations between vegetation productivity, climate change, and grazing disturbance (e.g., livestock number and meat production), we also aim to identify their relative contributions to alpine grassland dynamics, and to discuss the potential regulations in livestock management and grassland conservation.

Table 1. Main acronyms of productivity terms and their meanings used in this study.

Acronym	Definition
NPP	net primary productivity
NPP_P	potential net primary productivity, only driven by climatic factors in each grassland type
NPP_A	actual net primary productivity, driven by climatic factors and vegetation index livestock grazing in each grassland type
NPP_{pc}	defined as NPP_P-NPP_A, the proportion of grassland productivity that can be potentially consumed by livestock
NPP_{ac}	the proportion of grassland productivity that has been consumed by livestock. It can be estimated from forage consumed by livestock for body growth and meat output
NPP_{gap}	defined as NPPpc-NPPac. Nine scenarios of the mean and the trend of NPP_{gap} were summarized in Table 2

2. Materials and Methods

2.1. Study Area

The Northern Tibetan Plateau (NTP) is the most traditional and important semi-nomadic region in the Tibetan Autonomous Region, China. In this region, 176,337 herdsmen and 8,941,500 domestic animals live on the 5.2×10^5 square kilometers of available alpine pastures as of 2011 [22]. Livestock husbandry is the dominant economic activity and the major source of income for the herdsman families in this region, generally accounting for 74%–93% of their annual gross income [22]. Livestock grazing is an extensive anthropogenic disturbance in NTP, so this region is increasingly accepted as the most ideal region for studying feedback between vegetation, climate, and grazing on the Qinghai-Tibetan Plateau [23–25]. Across NTP, plants generally start to grow in early May and to senesce in late September, with up to 85% of annual precipitation falling and mean daily temperature being over 5.0 °C during this period [24]. Three zonal alpine grassland types are encountered moving from east to west, from humid alpine meadow (AM) dominated by *Kobresia pygmaea* (a sedge species), to semi-arid alpine steppe (AS) dominated by *Stipa purpurea*, and to arid alpine desert-steppe (ADS) co-dominated by *S. purpurea* and *S. glareosa* [24,26].

2.2. Simulated Potential and Actual Grassland Productivity

In this study, we used the Terrestrial Ecosystem Model (TEM) and the Carnegie–Ames–Stanford Approach (CASA) model, respectively, to simulate the potential and actual net primary productivity ($\mathrm{NPP_P}$ and $\mathrm{NPP_A}$) [8]. The former is a process-based ecosystem model and driven by spatially referenced information on vegetation type, climate, elevation, soil water and nutrient availability. The latter is based on remote sensing and climate datasets, with actual influence of human activities being included in remote sensing data. Formulae in TEM and CASA models for NPP calculation are as follows, and detailed parameters can be found in our previous work [8]. In this study, the difference between $\mathrm{NPP_P}$ and $\mathrm{NPP_A}$ was defined as the productivity that can be potentially consumed ($\mathrm{NPP_{pc}}$) by domestic animals and wild herbivores.

$$\mathrm{GPP} = (\mathrm{C}_{max}) \frac{\mathrm{PAR}}{\mathrm{PAR} + \mathrm{k_i}} \frac{\mathrm{C_i}}{\mathrm{k}_c + \mathrm{C}_i} (\mathrm{TEMP})(\mathrm{KLEAF}) \tag{1}$$

$$\mathrm{NPP_P} = \mathrm{GPP} - \mathrm{R_a} = \mathrm{GPP} - \left(\mathrm{R_m} - \mathrm{R_g}\right) \tag{2}$$

$$\mathrm{NPP_A} = \mathrm{APAR} \times \varepsilon = \mathrm{fPAR} \times \mathrm{PAR} \times \varepsilon^* \times \mathrm{T}_\varepsilon \times \mathrm{W}_\varepsilon \tag{3}$$

$$\mathrm{NPP_{pc}} = \mathrm{NPP_P} - \mathrm{NPP_A} \tag{4}$$

2.3. Productivity Actually Consumed by Domestic Herbivores

The number of livestock inventoried at year-end and the quantity of meat output including beef and mutton at the county level over NTP were taken from the Tibet Statistic Yearbooks [22]. The absolute numbers of different domestic animals (yaks, sheep, goats and horses) were firstly converted to standardized sheep units [6]. The actually consumed productivity ($\mathrm{NPP_{ac}}$) included the productivity consumed by the inventoried livestock ($\mathrm{NPP_{livestocck}}$) and the productivity consumed for meat output ($\mathrm{NPP_{meat}}$).

$$\mathrm{NPP_{ac}} = \mathrm{NPP_{livestock}} + \mathrm{NPP_{meat}} \tag{5}$$

$$\mathrm{NPP_{livestock}} = 0.45 \times \text{daiy intake per sheep unit} \times \text{Livestock} \tag{6}$$

$$\mathrm{NPP_{meat}} = 0.45 \times (71.38 \times \text{Yak meat} + 65.07 \times \text{Mutton}) \tag{7}$$

$\mathrm{NPP_{livestock}}$ and $\mathrm{NPP_{meat}}$ were estimated following the approach of Pan et al. [21]. $\mathrm{NPP_{livestock}}$ was estimated from the daily forage intake per standardized sheep unit, about 1.8 kg dry matter per day [27]. $\mathrm{NPP_{meat}}$ was estimated by coefficients of gross dry matter consumption per meat weight as reported Pan et al. [28]. In Equations (6) and (7), 0.45 is the coefficient to transform dry matter to carbon. NPP_{ac} was also standardized to g C/m^2, referring to the area of available pastures at the county level (Supplementary Table S1), and finally converted to annual grid surfaces as the ratio of total NPP_{ac} to the summed area of available pasture for each county.

2.4. Precipitation and Temperature Data

Daily mean temperature and total precipitation records between 1993 and 2011 were provided by the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). We aggregated daily climatic records to monthly averages, interpolated and re-aggregated into 8 km × 8 km grids using the ANUSPLIN 4.2 [29] to match the spatio-temporal resolution of the productivity datasets used in this study. The quality of grid climatic surfaces has been demonstrated by the very high correlations to field observation records [8,30]. The average temperature (GST) and sum precipitation (GSP) during the annual plant growth season (generally from May to September) were calculated for time series analysis. Annual and non-growing season average temperatures (MAT and NGST) and sum precipitations (MAP and NGSP) were also provided. In this study, to calculate NPP_A, the NDVI data from 1993 to 2000 was obtained from an advanced very high resolution radiometer (AVHRR) dataset, which was developed by the Global Inventory Modeling and Mapping Studies (GIMMS) group (http://glcf.umd.edu/data/gimms/) while the data from 2001 to 2011 was downloaded from the moderate-resolution imaging spectroradimeter (MODIS) product (MYD13A2.5) (https://lpdaac.usgs.gov/get_data/data_pool). Detailed information on data processing methods including resampling and smoothing can be found in Chen et al. [8].

2.5. Time Series Analyses

The method of comparing trends between NPP_P and NPP_A has been widely adopted in identifying the direction of natural and human influences, and in assessing the magnitude of various divers on long-term vegetation trends [8,20,21,31,32]. In each dataset, the temporal trend across the entire study period of 19 years was calculated with Equation (8).

$$Slope_{data} = \frac{n \times \sum_{i=1}^{n}(i \times data_i) - \sum_{i=1}^{n} i \times \sum_{1}^{n} data_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{8}$$

The significance of the variation tendency was determined by F-test [20]. The calculation for F-statistics is expressed as follows:

$$\mathrm{F} = \mathrm{U} \times \frac{n-2}{\mathrm{Q}} \tag{9}$$

$$\mathrm{U} = \sum_{i=1}^{n}(\hat{y}_i - \overline{y})^2 \tag{10}$$

$$\mathrm{Q} = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{11}$$

$$\hat{y}_i = \mathrm{Slope} \times \mathrm{i} + \mathrm{b} \tag{12}$$

$$\mathrm{b} = \overline{y} - \mathrm{Slope} \times \mathrm{i} \tag{13}$$

where U is the residual sum of the squares; Q is the regression sum; $\hat{y}_i$ is the regression value, which can be calculated by Equations (17)–(19); y_i is the observed value of year I; $\overline{y}_i$ is the mean value over n years; and b is the intercept of the regression formula.

For bivariate analysis at each pixel, the correlations of productivity indicators with GST and GSP, respectively were also explored by the Pearson correlation techniques as shown in Equation (14):

$$r = \frac{n \times \sum_{i=1}^{n}(X_i \times Y_i) - (\sum_{i=1}^{n} X_i)(\sum_{i=1}^{n} Y_i)}{\sqrt{n \times \left(\sum_{i=1}^{n} X_i^2\right) - (\sum_{i=1}^{n} X_i)^2}\sqrt{n \times \left(\sum_{i=1}^{n} y_i^2\right) - (\sum_{i=1}^{n} Y_i)^2}} \quad (14)$$

where n is the sequential year and X_i and Y_i represent productivity and climate variable, respectively.

We did not directly disentangle their relative contributions to vegetation dynamics in a generalized linear model with analysis of variance (co-variance) because of the coarser spatial resolution of the grazing activities and available pasture area datasets compared to plant productivity values. Instead, we used the mean value of NPP_{gap} (termed as $NPP_{pc} - NPP_{ac}$) and its tendency to describe the direction and magnitude of productivity change. Here, we mainly focused on the nine NPP_{gap} variation scenarios as shown in Table 2, to find some potential implications on stocking rate regulation for pasture conservation in the future.

Table 2. The nine scenarios of the mean and the trend of NPP_{gap} (defined as $NPP_{pc} - NPP_{ac}$) at the pixel scale from 1993 to 2011.

Mean	Trend	Vegetation Status	Current Stocking Rate	Future Stocking Rate
=0	>0	Healthy	Reasonable	Can be increased
	=0	Healthy & stable	Reasonable	No regulation
	<0	Healthy	Reasonable	Need to be reduced
>0	>0	Restored	Low	Should be increased
	=0	Restored & stable	Low	No regulation
	<0	Restored	Low	Must not be increased
<0	>0	Degraded	Overgrazed	Should be reduced
	=0	Degraded &stable	Overgrazed	Must be reduced

3. Results

3.1. Trends of Precipitation and Temperature from 1993 to 2011

From 1993 to 2011, temperatures significantly increased across nearly the entire Northern Tibetan Plateau (NTP) (Figures 1 and 2). In the north-central and eastern regions, GST and NGST have significantly risen by 0.08 °C/year–0.09 °C/year and 0.12 °C/year–0.14 °C/year, respectively. In its western, south-central and south-eastern regions, the warming rate during the plant growing season was relatively lower, at approximately 0.04 °C/year–0.06 °C/year. In general, MAT has a similar spatial pattern of long-term trend to GST. Evident spatial variability in precipitation was also observed across the entire NTP (Figure 1). However, significant increasing trends of GSP and MAP were observed only in the north-eastern NTP (Figure 2). In its central and western parts, no significant increase was found for either GSP or MAP. NGSP was observed to significantly decrease in the only three south-eastern counties, Lhari, Biru and Sog (Appendix Figure A1, map (b) for current administrative county boundary).

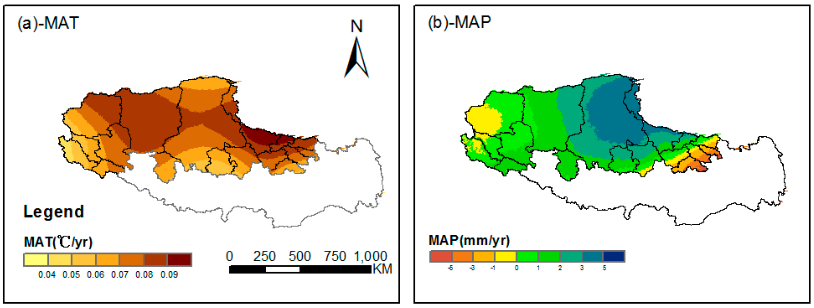

Figure 1. *Cont.*

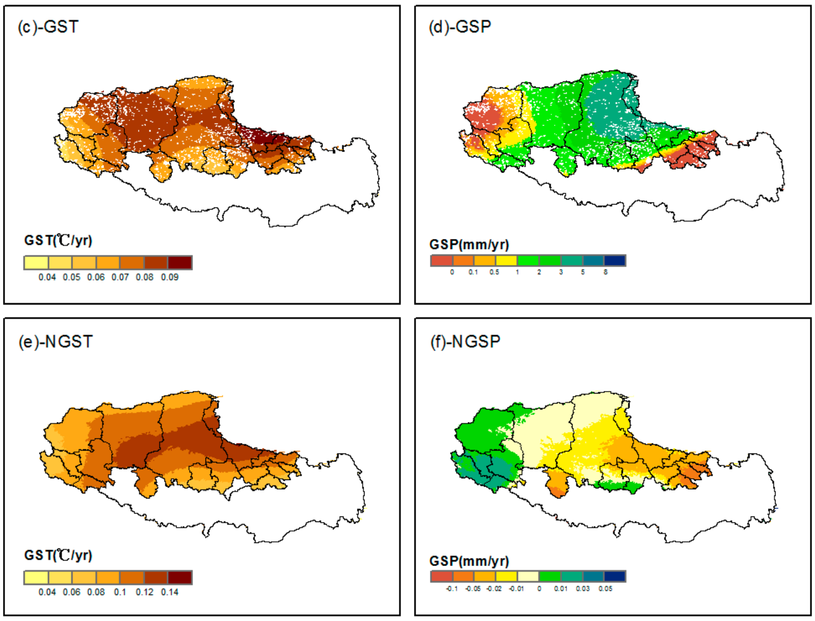

Figure 1. Trends of climatic variables from 1993 to 2011 across the Northern Tibetan Plateau (NTP). (**a**) mean annual temperature (MAT); (**b**) mean annual precipitation (MAP); (**c**) growing season temperature (GST); (**d**) growing season precipitation (GSP); (**e**) non-growing season temperature (NGST); and (**f**) non-growing season precipitation (NGSP).

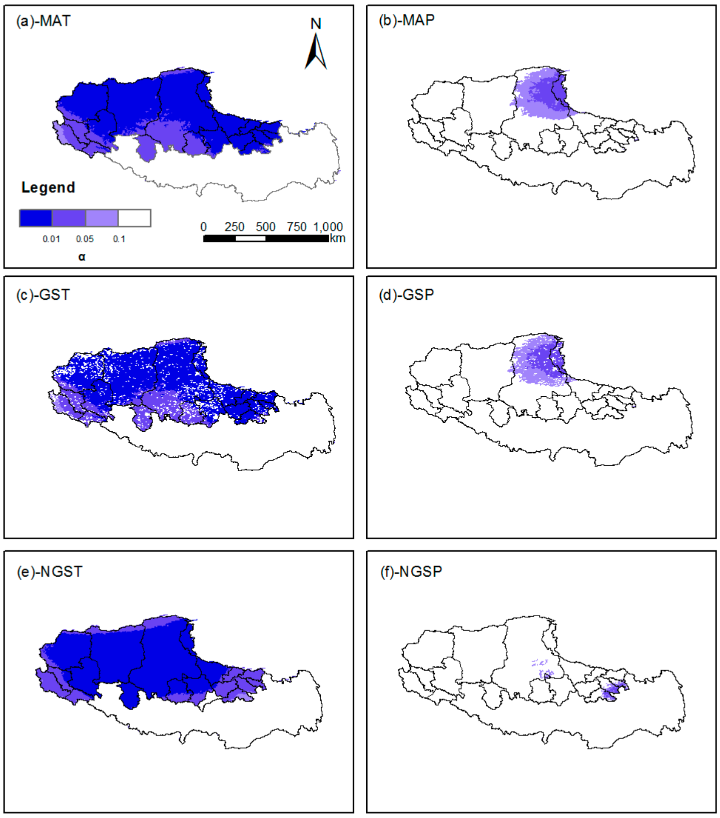

Figure 2. The significance of the corresponding climatic trends from 1993 to 2011 across the Northern Tibetan Plateau (NTP). (**a**) Mean annual temperature (MAT); (**b**) mean annual precipitation (MAP); (**c**) growing season temperature (GST); (**d**) growing season precipitation (GSP); (**e**) non-growing season temperature (NGST); and (**f**) non-growing season precipitation (NGSP).

3.2. Trends of Simulated and Consumed Productivity from 1993 to 2011

Significant increasing trends of NPP_P (Trend > 0, Figure 3a; $P < 0.05$, Figure 4a) were found for 29.63% of alpine grasslands that were mainly distributed in the northern NTP, with an increasing rate up to 5 g C/m^2/year, while in the southern and western regions no evident trend was observed for NPP_P (Figures 3a and 4a). Only 7.84% of pasture patches showed a significant increasing trend in NPP_A, scattering across the entire NTP (Figures 3b and 4b). The increasing trend of NPP_{pc} was observed to be nearly coincident with NPP_P, accounting for 28.8% of pixels across the entire NTP (Figures 3c and 4c). From 1993 to 2011, NPP_{ac} showed significant increasing trends in nearly all the counties except Burang, Biru, Sog and part of Gerze (Figures 3d and 4d. See Appendix Figure A1, map (b) for the current administrative county boundary).

3.3. Correlations of Actual and Potential Productivity with Climate from 1993 to 2011

No significant relation was found between NPP_{pc} and GST, with their correlation coefficient for 87.20% of the pixels being between −0.5 and 0.5 across the entire NTP (Figure 5a). NPP_{pc} was found to be positively correlated with GSP, with their correlation coefficient being over 0.8 for 59.70% of pixels (Figure 5b). There was no evident correlation between NPP_{ac} and climatic variables at the county level across the entire NTP (Figure 5c,d). The interior difference of the correlation of NPP_{ac} with climatic variables within Gerze and Nyima might be due to the historical adjustments of county boundaries (See for the maps of boundary changes between administrative counties before and after 2002 in this region).

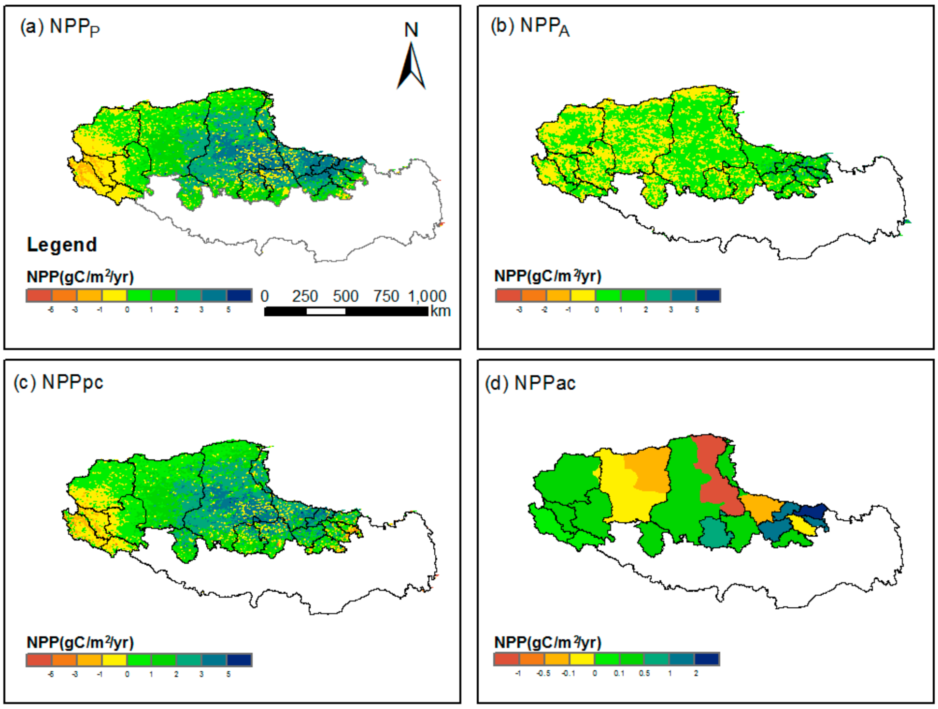

Figure 3. Trends of simulated or calculated grassland productivity from 1993 to 2011. Map (**a**) shows the trend of potential net primary productivity (NPP_P), which was from the Terrestrial Ecosystem Model and driven only by climate variables. Map (**b**) shows the trend of actual net primary productivity (NPP_A), which was simulated by the Carnegie–Ames–Stanford Approach (CASA) model with remote sensing data as the driving variables and can reflect the actual productivity after biomass partly consumed by livestock or wild herbivores. Map (**c**) shows the trend of the difference between NPP_P and NPP_A, which was defined as the productivity proportion that can be potentially consumed by livestock (NPP_{pc}). Map (**d**) shows the trend of NPP_{ac}, which reflected the productivity actually consumed by livestock or converted to meat for human society.

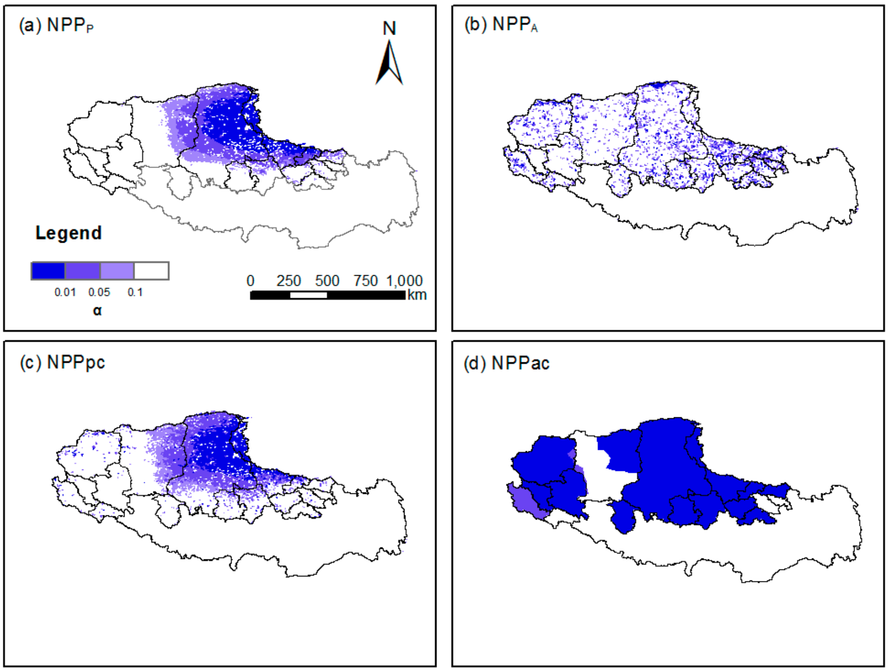

Figure 4. The significance levels of potential net primary productivity (NPP_P) from 1993 to 2011 (**a**); Map (**b**) shows the significance levels of actual net primary productivity (NPP_A); Map (**c**) shows the significance levels of the difference between NPP_P and NPP_A, which was defined as the productivity proportion that can be potentially consumed by livestock (NPP_{pc}); Map (**d**) shows the significance levels of NPP_{ac}, which reflected the productivity actually consumed by livestock or converted to meat for human society.

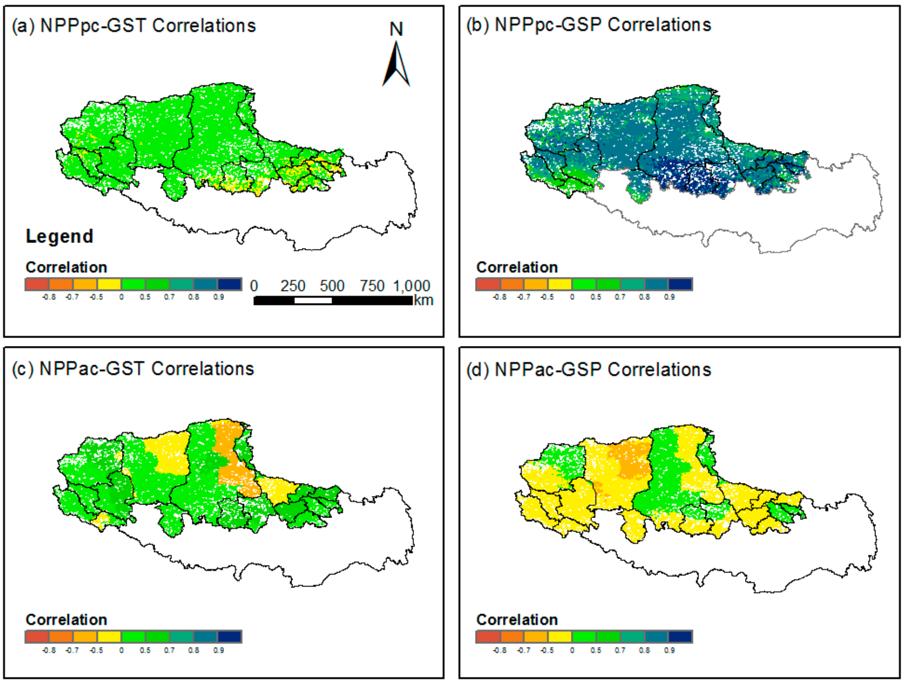

Figure 5. Correlations of net primary productivity that can be potentially consumed (NPP_{pc}, maps in (**a**,**b**) or that had been actually consumed by livestock (NPP_{ac}, maps in (**c**,**d**)) with average temperatures (GST, growing season temperature, maps in (**a**,**c**) and sum precipitation (GSP, growing season precipitation, maps in (**b**,**d**)).

3.4. Trend, Significance and Climatic Dependency of NPP$_{gap}$ from 1993 to 2011

Implications for stocking rate regulation were summarized in Table 3. Mean annual NPP$_{gap}$ for 29.65% of available alpine grasslands was negative, indicating overgrazing and calling for a reduce in stocking rate. About 69.05% of available alpine pastures are healthy or have been restored, indicating that the current stocking rates are at low or moderate levels. For 58.74% of alpine pastures, therefore, the stocking rates are suggested to increase in future because grasslands there are likely getting better due to the positive mean NPP$_{gap}$ and its increasing trend. On the other hand, 16.37% of alpine grasslands need to be excluded from animals grazing, because both the negative mean NPP$_{gap}$ and the decreasing trend imply that the grassland likely degrades even further (Table 3). NPP$_{gap}$ for 15% of pixels was found to significantly increase in the most north-eastern areas (Figure 6a,b). For 4.4% of pixels NPP$_{gap}$ significantly decreased, but the decrease in the western and south-eastern NTP parts was not significant (Figure 6a,b). In general, NPP$_{gap}$ was not correlated with GST because the correlation coefficient for most pixels was between -0.5 and 0.5 (Figure 6c). However, for 65.9% of pixels NPP$_{gap}$ was highly dependent on GSP, where the correlation coefficient being higher than 0.8 (Figure 6d).

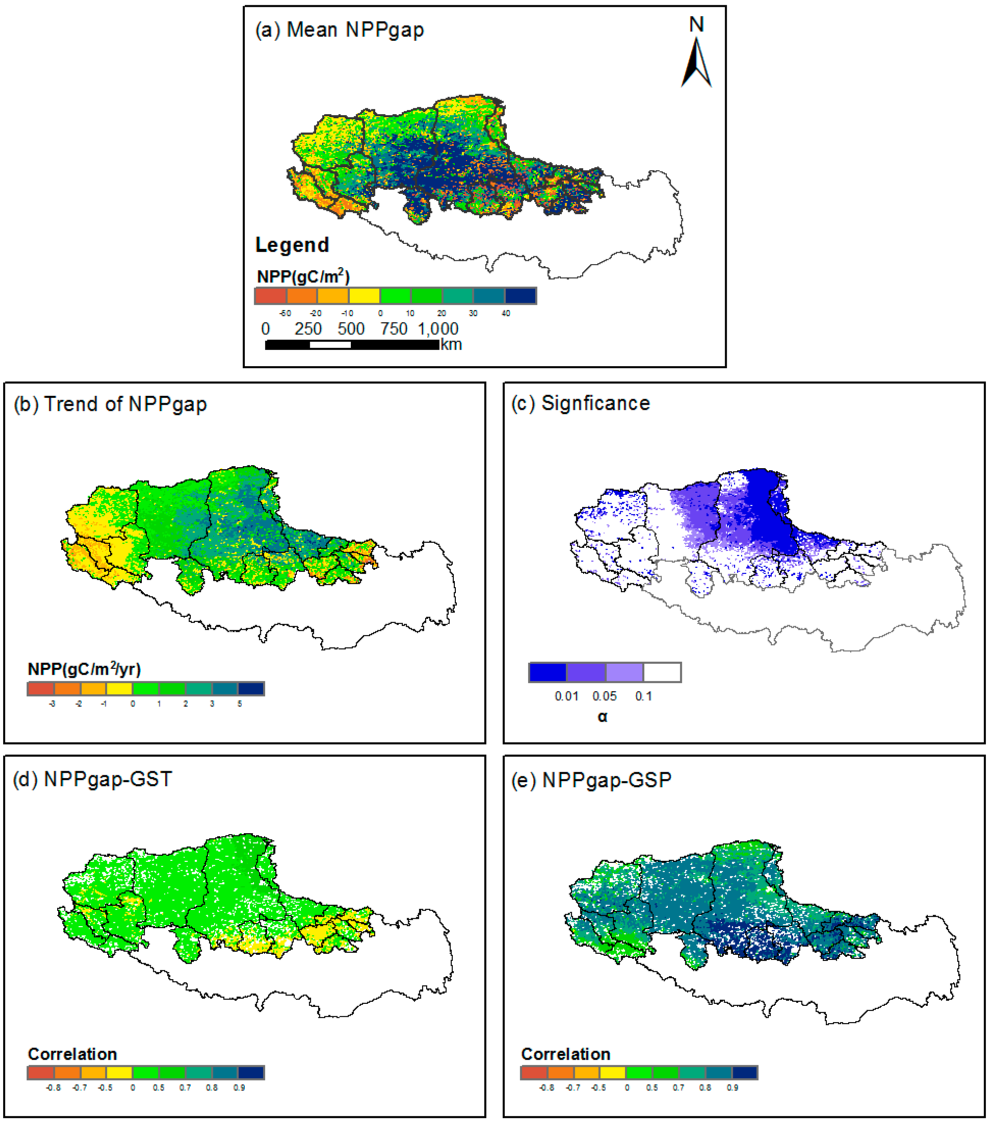

Figure 6. (**a**) Mean values, (**b**) trends and (**c**) the corresponding significance levels of NPP$_{gap}$ from 1993 to 2011. Maps in (**d**) and (**e**) showed the correlation coefficients of NPP$_{gap}$ with air temperature average (GST) and total precipitation (GSP) during the plant growing season, respectively.

Table 3. Summary of the area and the corresponding proportion of NPP_{gap} in different trends (>0, =0, and <0) and different means (>0, =0, and <0) for the nine scenarios proposed as Table 2 in this study.

Mean	Trend	The Target Area (km^2)	The Percentage (%)
=0	>0	0	0
	=0	0	0
	<0	0	0
>0	>0	405,349	58.74
	=0	0	0
	<0	71,162	10.31
<0	>0	91,648	13.28
	=0	0	0
	<0	112,974	16.37

4. Discussion

Alpine grasslands on the Tibetan Plateau are extremely sensitive to climate variation and human activities because of their vulnerability and severe physical conditions in this region [5]. The ongoing climate warming and historical overgrazing are considered to be main drivers for alpine pasture degradation there [4,8]. Adaptive strategies and sustainable policies are increasingly called for with respect to alpine pasture conservation faced in a developing Tibet [6]. In addition, it is a big challenge to identify, disentangle, and assess the relative contribution of climate and anthropogenic variables to variability in ecosystem functionality, but it is also increasingly required [33].

Wessels et al. [34] proposed a method of defining land capability units coupled with the normalized difference vegetation index (NDVI) to distinguish natural variables from anthropogenic influences. Similarly, Li et al. [35] identified and assessed vegetation changes that were mainly induced by human acuities in temperate grasslands in Inner Mongolia using a temporal NDVI residual trend method. In two recent studies, Chen et al. [8] and Wang et al. [20] accepted the difference between potential and actual productivity of alpine grasslands that were simulated by theoretical and remote sensing-based models, respectively, to represent the intensity of human influences. For example, Wang et al. [20] reported that 61.2% of the total grassland area experienced restoration from 2001 to 2013 on the Qinghai-Tibetan Plateau and that human activities, climate variation, and their combined effect accounted for 28.6%, 12.8% and 19.9% of the restored alpine grasslands with increasing productivity.

However, a major shortcoming still remains in the hypotheses of both Chen et al. [8] and Wang et al. [20] in that grassland productivity dynamics are only affected by climate and human activities, with the potential plant regrowth within the same season after livestock grazing being ignored. A multi-site survey with fenced versus grazed paired plots across the northern Tibetan Plateau also found that the differences in aboveground productivity were not only controlled by climate variables but also influenced by grazing management and closely related to plant community properties [13,36,37]. Therefore, the proportion of grassland productivity consumed by livestock should be included in remote-sensing based models for simulating grassland productivity, to represent the actual grassland productivity that has really been influenced by both climate change and human activities. Pan et al. [21] proposed a modified framework for assessing the climate and human impacts on grassland productivity on the Tibetan Plateau, in which the proportion of productivity appropriated by human society was estimated from current-year livestock inventories and meat production with specific transform coefficients for yak and sheep, respectively. Thus, the difference between potential and actual productivity, stimulated by theoretical (mechanism) models and by remote-sensing models, respectively, can be used not only to indicate the relative contribution of natural and anthropogenic factors, but also to reasonably direct the livestock regulation under differential climate change scenarios.

Previous studies suggested that temperature and precipitation showed increasing trends on the Tibetan Plateau, giving an increasing rate of air temperature nearly double that of the last fifty years [38] and three times the global warming rate [5,39]. In contrast, the precipitation exhibited different patterns within the entire Qinghai-Tibetan Plateau, differing among zonal alpine grassland types [8,9], which was accepted to mainly drive the differential response of vegetation phenology to climate changes. We found that only 29.63% of alpine grasslands exhibited significant increasing trends of NPP_P with an average rate up to 5 g·C/m^2/year (Figures 3a and 4a) mainly distributed in the northern NTP, where precipitation during the plant-growing season also significantly increased from 1993 to 2011 (Figures 1d and 2d). Although significant climate warming was observed over the entire northern Tibetan Plateau (Figures 1 and 2), no significant correlation was found between NPP_{pc} and GST for 87.2% of alpine grassland pixels across the entire NTP (Figure 5a). NPP_{pc} was found to be positively correlated with GSP for 59.7% of grassland pixels (Figure 5b). Therefore, our study further confirmed that precipitation is the primary driving force in the edges of the northern Tibetan Plateau, consistent with both remote sensing research [9] and field surveys [11,13,37] in this region. Although NPP_{ac} was found to have no correlation with either GSP or GST, the mosaic pattern of correlation coefficient differs among different counties (Figure 5c,d) and implies that stocking rate and pasture management likely affect the actual productivity of alpine grasslands in this region.

In 2003, the government started to construct metal fences on severely degraded pastures [4]. A new compensatory payment policy was launched in 2011, according to which local herding families can be compensated for alpine pasture conservation if these policies are maintained and effectively administered. Therefore, the degraded grasslands are expected to rapidly recover in the future. Current studies consistently indicate that climate changes, especially in precipitation during the plant growing months, likely limit the spatio-temporal dynamics of forage productivity of alpine grassland on the Tibetan Plateau [9,11,13]. However, these studies cannot offer more mechanistic knowledge or clearer indications on how to make livestock management more reasonable. For example, Chen et al. [8] reported that the area percentage of grassland productivity changes mainly resulting from human activities doubled from 20.16% between 1982 and 2001 to 42.98% between 2002 and 2011. We found the gaps between potential and actual productivity differed regionally, which may reflect differences in alpine grassland types that are dominated by different plant species [37,40]. Similarly, Liang et al. [41] found that alpine grassland biomass in the pastoral area of southern Qinghai Province, a region in the central-eastern Qinghai-Tibetan Plateau, shows considerable spatial heterogeneity because of the geographical, topographical, climatic and biophysical limitations. In this study, NPP_{gap} was included in the assessment framework for evaluating the relative contributions of climate change and grazing activities. The long-term width variation of NPP_{gap} was additionally introduced to identify the directions of vegetation change, restoration or degradation. We even found that the mean NPP_{gap} was positive, negative, zero or a mixture of all over the entire study region, with either increasing, decreasing or invariant trends over the defined period. Here, we point out that uncertainties still remain about the direction of livestock management trends because the spatial scale of data concerning grazing pressure at the county level was coarse.

5. Conclusions

In summary, our study clearly documented recent changes in grassland productivity and analyzed the potential impacts of temperature, precipitation and stocking density on vegetation dynamics. Although precipitation only significantly increased in the northern areas, accounting for a smaller proportion of grasslands over the entire study region, precipitation is still the primary driving force for productivity dynamics during the study period. Due to a decrease in stocking density, the gap between potential and actual consumed productivity increased in the central parts of the northern Tibetan Plateau, suggesting that the stocking rate can be increased in alpine grasslands under restoration processes. Due to the coarse scale of livestock-related variables in this study, some uncertainties remain about the direction of alpine grassland dynamics. However, we found that about 69.05% of available alpine pastures are healthy or have been restored, and are listed as having low or moderate stocking rates in the central parts of the northern Tibetan Plateau.

Supplementary Materials: The following are available online at www.mdpi.com/2072-4292/9/2/136/s1, Table S1: The records of livestock inventory, production of yak meat and mutton, available pastures at the county level on the Northern Tibetan Plateau.

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Author Contributions: Jianshuang Wu conceived and designed this research; Xianzhou Zhang provided the datasets; Yunfei Feng analyzed the data and prepared the figures. Jianshuang Wu and Yunfei Feng wrote the manuscript; Jing Zhang, Xianzhou Zhang and Chunqiao Song contributed to the interpretation of the results. All the authors have contributed to this work.

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Appendix A

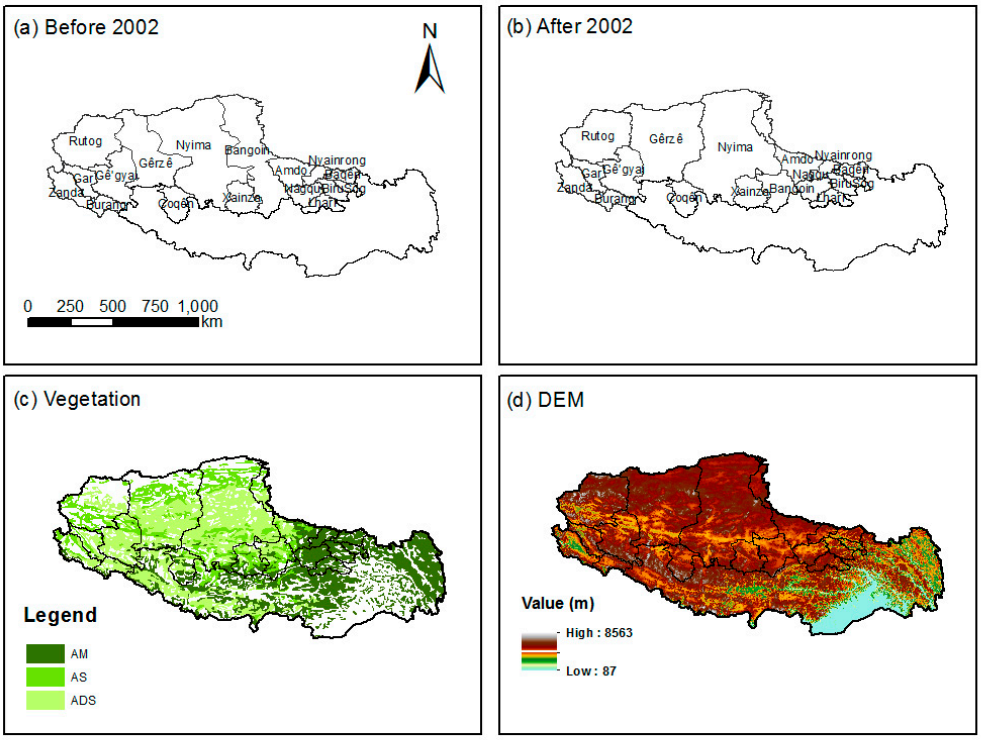

Figure A1. Map (**a**) is for the administrative county boundary before year 2002; Map (**b**) is for the current administrative county boundary after year 2002; Map (**c**) is the vegetation type of Tibet, there are alpine meadow (AM), alpine steppe (AS), and alpine desert steppe (ADS), respectively; Map (**d**) is the elevation of Tibet.

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