remote sensing

MDPI

Article

The Influences of Climate Change and Human Activities on Vegetation Dynamics in the Qinghai-Tibet Plateau

Ke Huang [1,2], Yangjian Zhang [1,3,*], Juntao Zhu [1,*], Yaojie Liu [1,2], Jiaxing Zu [1,2] and Jing Zhang [4]

1 Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; huangk.13b@igsnrr.ac.cn (K.H.); liuyj.14b@igsnrr.ac.cn (Y.L.); zujx.15b@igsnrr.ac.cn (J.Z.)
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China
4 College of Global Change and Earth System Sciences, Beijing Normal University, Beijing 100875, China; jingzhang@bnu.edu.cn
* Correspondence: zhangyj@igsnrr.ac.cn (Y.Z.); zhujt@igsnrr.ac.cn (J.Z.); Tel./Fax: +86-10-6488-9703 (Y.Z.)

Academic Editors: Rasmus Fensholt, Stephanie Horion, Torbern Tagesson, Martin Brandt, Jose Moreno, Clement Atzberger and Prasad S. Thenkabail
Received: 30 June 2016; Accepted: 18 October 2016; Published: 23 October 2016

Abstract: Grasslands occupy nearly three quarters of the land surface of the Qinghai-Tibet plateau (QTP) and play a critical role in regulating the ecological functions of the QTP. Ongoing climate change and human interference have greatly affected grasslands on the QTP. Differentiating human-induced and climate-driven vegetation changes is vital for both ecological understanding and the management of husbandry. In this study, we employed statistical analysis of annual records, various sources of remote sensing data, and an ecosystem process model to calculate the relative contribution of climate and human activities to vegetation vigor on the QTP. The temperature, precipitation and the intensity and spatial pattern of livestock grazing differed between the periods prior to and after the year 2000, which led to different vegetation dynamics. Overall, increased temperature and enhanced precipitation favored vegetation growth. However, their combined effects exhibited strong spatial heterogeneity. Specifically, increased temperature restrained vegetation growth in dry steppe regions during a period of slightly increasing precipitation from 1986 to 2000 and in meadow regions during a period of precipitation decline during 2000–2011, thereby making precipitation a dominant factor. An increase in precipitation tended to enhance vegetation growth in wet meadow regions during warm periods, and temperature was the limiting factor in Tibet during dry periods. The dominant role played by climate and human activities differed with location and targeted time period. Areas dominated by human activities are much smaller than those dominated by climate. The effects of grazing on grassland pasture were more obvious under unfavorable climate conditions than under suitable ones.

Keywords: grassland; climate change; grazing; contribution; multiple standardize regression

---

1. Introduction

As a dominant terrestrial ecosystem on the Qinghai-Tibet Plateau (QTP), grasslands play a pivotal role in linking the pedospheric, atmospheric, and hydrospheric systems in the region, and even the whole of Asia [1–5]. Meanwhile, effects of global climate change have been reported to be more obvious in regions of high altitude [6–9]. With a mean elevation of approximately 4000 m above sea level, temperature on the plateau has been increasing at a much faster rate than in most other regions in the world [10,11]. In addition, as a traditional mode of land use on the plateau [11], livestock husbandry has developed rapidly over the past several decades, contributing to significant environmental and grassland degradation [12]. In order to recover and protect the environments on the plateau, during the late 20th century, the Chinese government implemented a series of projects, including grazing exclusion and establishment of national conservation areas. To maximize the effectiveness of these projects, regular monitoring of grassland dynamics and identifying its underlying mechanisms are necessary. Knowledge gained therefrom can also be used as a basis for sound policy making.

Due to its capability in measuring chlorophyll and energy absorption, the Normalized Difference Vegetation Index (NDVI) has been widely used as an indicator of numerous vegetative biophysical parameters, such as biomass and productivity [13–15]. For regional scale studies, the NDVI derived from satellite data can be readily accessed by a wide array of instruments. Recently, the Advanced Very High Resolution Radiometer (AVHRR) developed by the National Oceanic and Atmospheric Administration (NOAA) generated the third-generation Global Inventory Modeling and Mapping Studies (GIMMS3g) NDVI dataset [16]. Due to its superior performance relative to prior versions and its capability for providing the longest time-series record from the early 80s, the GIMMS3g dataset has been widely used to identify vegetation activity trends and relationships with climatic factors [17,18]. However, studies have suggested that the GIMMS NDVI time-series should be dealt with cautiously when being applied to semiarid and sparsely vegetated areas such as the Sahel and the Tibetan Plateau, since the data have been identified as being biased in these regions [19,20]. To overcome this limitation, it is necessary to better integrate optional data sources [21]. Since the late 90s, improved sensors are being designed specifically for vegetation monitoring, exemplified by the Terra MODIS (Moderate Resolution Imaging Spectro-radiometer), whose NDVI time-series have been successfully utilized as surrogates for the GIMMS3g dataset in regions where GIMMS3g data is biased [22,23].

To date, numerous studies have analyzed inter-annual variations of the NDVI and their relationship to temperature and precipitation throughout the QTP [24,25]. It was found that grassland productivity has been significantly influenced by climate change on the plateau [26,27]. Elevated temperature has favored grassland growth [21]. Precipitation has been identified as a potential factor driving annual maximum NDVI variability for meadows and grasslands with medium vegetation cover [28]. The growing season NDVI of the steppe is driven by both temperature and precipitation [29]. In addition, effects of precipitation and temperature on vegetation growth have been found to exhibit strong spatial heterogeneity throughout the arid and semi-arid regions [30,31]. In the headstream region of Yangtze River, overgrazing has resulted in severe grassland degradation [32], whereas at the same time some researchers have pointed out that light-intensity grazing improves alpine meadow productivity and promotes adaptation to environment change on the plateau [33]. The contradictory findings indicate that livestock husbandry exerts significant effects on grassland ecosystems contributing to high spatial heterogeneity over the entire plateau.

To the authors' best knowledge, previous studies have not distinguished anthropogenic drivers and climate drivers at the county level on a geographic scale. The respective effects of human activity and climate on vegetation growth still remain unclear. In particular, knowledge related to the contributions arising from anthropogenic factors remains extremely scarce due to the absence of data on the intensity of anthropogenic activities. A thorough understanding of the relative contribution of each driving factor is essential for developing sustainable management capable of coping with consequences of climate change. In this study, we used the satellite-based vegetation index NDVI and the climatic dataset along with data on livestock grazing intensity to explore co-variations between vegetation dynamics and environmental variables across the QTP grasslands. Since statistical data on stocking intensity is available only for the years 1986–2011, this study is focused mainly on this 26-year period. The principal objectives of this research have been to: (1) Quantify the spatial and temporal variations of vegetation dynamics in response to climate change and anthropogenic activities on the plateau; (2) Identify the dominant factors regulating vegetation dynamics of the QTP grasslands prior to and post 2000.

2. Materials and Methods

2.1. Study Area

The Qinghai-Tibet Plateau lies in the central part of the "Third Pole". The plateau is located in the semi-arid/arid alpine climate zone, with an annual precipitation of about 250 mm. For the coldest, the mean temperature is lower than −5 °C and for the warmest month it is lower than 10 °C, respectively. The plateau is separated by the Tanggula Mountains into two zones, along a rainfall gradient from 50 to 200 mm in the western Tibet Autonomous Region (Tibet) to 200–500 mm in the east, including the province of Qinghai [34]. There is also a precipitation gradient from 50 to 150 mm in the southeast to 300–450 mm in the northwest. Grassland, occupying nearly 75% of the plateau, is the dominant vegetation type on the QTP (Figure 1). For alpine grasslands, pasture for sheep and yaks is the most common anthropogenic activity [35]. Since the early 1990s, governments have launched a series of projects to cope with environmental degradation. Nearly one third of the grasslands on the plateau is protected under the delineation of National Conservation Areas (NCAs). There are three NCAs on the plateau, including the Qiangtang Wildlife Sanctuary, the Kekexili National Reserve and the Sanjiangyuan National Nature Reserve, which were established in 1993, 1995, and 2000, respectively. In addition, each of the counties' boundary in the two provinces were regrouped into seven major subzones with reference to the climatic zone, topography, and the national reserve of the Qinghai-Tibet Plateau (Figure 1).

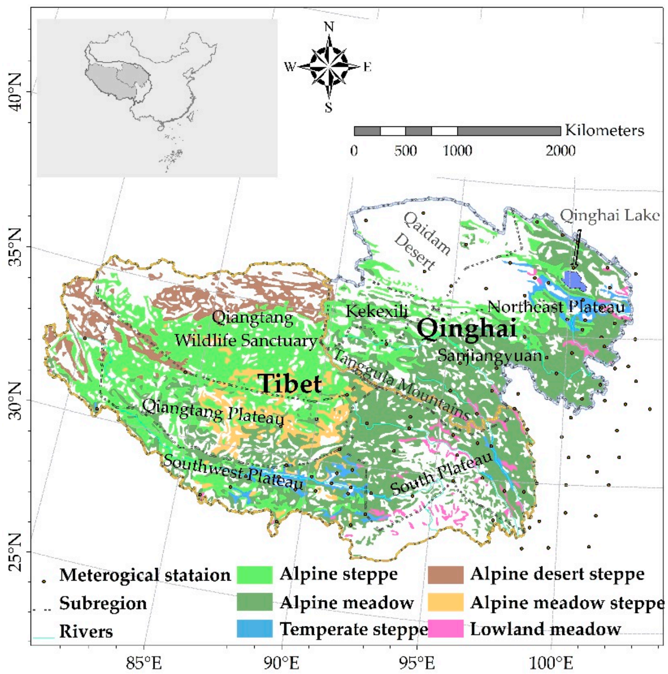


Figure 1. The study region and meteorological stations for different grassland types.

2.2. Data

2.2.1. Meteorological Data

Monthly precipitation and air temperature datasets during the period of 1986–2011 were collected from the Chinese Meteorological Data Service [36]. In total, data from 75 meteorological stations were utilized (Figure 1). The original meteorological data was interpolated to continuous surface data with an 8 km spatial resolution using the AUSPLINE interpolation program [37]. We used the growing season accumulative precipitation (GSP) and growing season mean temperature (GST) as the two main factors influencing climate for each county.

2.2.2. NDVI Time Series

Recognizing that the data may reflect biases in the GIMMS3g NDVI dataset on the Qinghai-Tibet Plateau after the year 2000, we used 8 km and 15-day composite GIMMS3g data [38] for 1986–2000, and both GIMMS3g data and the 1 km and 16-day composite MODIS dataset (MOD13A2) [39] for the period of 2000–2011. Seven MODIS tiles—h24v05, h25v05, h25v06, h26v05, h26v06, h27v05, h27v06—are required for our study region. The MODIS tiles were mosaicked and then reprojected from the Sinusoidal projection to the Albers Conical Equal Area projection. Subset images for the study region were clipped from the GIMMS3g data and projected MODIS mosaics by the QTP boundary. Neither quality control data nor quality flag data were used in this study. The maximum value composite (MVC) method was used to select the higher value of bimonthly NDVI images for obtaining the monthly NDVI. Then, the monthly NDVI from May to September was averaged to yield the growing season NDVI (GSNDVI). GSNDVI images from 1986 to 2011 were developed in stacks for time-series analysis. We then extracted mean GSNDVI values from all pixels within each county's grassland for further analysis.

2.2.3. Livestock Grazing Intensity Data

The socio-economic data was acquired from the yearly statistical book, which provides statistical data at a county resolution. We obtained the livestock type and herd number data for 57 counties in Tibet and 21 counties around Sanjiangyuan in Qinghai Province from 1986 to 2011. The number of different animals from the Yearbooks was converted into sheep equivalent unit number (SUN) to quantify the stocking intensity within each county. Conventionally, 1 sheep and 1 goat equals 1 sheep unit, and other animals such as horses and yaks are equivalent to 5 sheep units [40,41]. We used the stocking intensity in 1986 and 2000 as the baseline stocking instensity for each county for 1986–2000 and 2000–2011. The time series for grazing intensity for these two periods was constructed using each year's grazing intensity relative to the year 1986 or 2000.

2.3. Analysis

2.3.1. Trend and Shift Trend Analysis

We utilized linear regression to detect the change rates of vegetation greenness (growing-season *NDVI*, *GSNDVI*), *GST*, *GSP* and livestock grazing intensity (LI) on the QTP during 1986–2000 and 2000–2011 at both regional and county scale. For example, the change rate for vegetation greenness was calculated as:

$$\theta_{slope} = \frac{n \times \sum_{i=1}^{n} i \times NDVI_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} NDVI_i}{\mathrm{n} \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \quad (1)$$

where when $\theta_{slope} > 0$, the vegetation greenness increased and vice versa.

The sequential Mann-Kendall (SQ-MK) test [42] was used to statistically assess whether there was a shift in trends of the climate-driving factors at a regional scale. The SQ-MK test, as a non-parametric "trend shift analysis" technology, has been increasingly applied to detect the change point in time series of vegetation greenness, temperature, vegetation phenology, etc. [43]. This test sets up two series, a progressive one $uf(t)$ and a backward one $ub(t)$. If they cross each other and diverge beyond a specific threshold value, then there is a statistically significant trend shift. For the GSP time series during 1986–2011, the application of the SQ-MK test has the following four steps in sequence:

1 For each comparison, the number of cases $\mathrm{GSP}_i > \mathrm{GSP}_j$ is counted and indicated by n_i at the i-th year, where GSP_i ($i = 1, 2, \ldots, n$) and GSP_j ($j = 1, \ldots, i-1$) are the sequential values in the inter-annual GSP series.

2 We defined the SQ-MK test statistic as t_i, which can be calculated as follows:

$$t_i = \sum_i n_i \quad (2)$$

3 The mean and variance of the test statistic are calculated using the following two equations, respectively.

$$E\left(t\right) = \frac{n \times (n-1)}{4} \tag{3}$$

$$Var\left(t_i\right) = \frac{i \times (i-1) \times (2 \times i + 5)}{72} \tag{4}$$

4 A sequential forward series $uf(t)$ value can be calculated via Equation (5):

$$uf\left(t\right) = \frac{t_i - E\left(t\right)}{\sqrt{Var\left(t_i\right)}} \tag{5}$$

Similarly, a sequential backward $ub(t)$ analysis of the SQ-MK test is calculated starting from the end of the time series data. The interception point of $uf(t)$ and $ub(t)$ can be compared with the threshold value to distinguish whether it is the significant trend shift point.

2.3.2. Explanation of Climatic Factors on Vegetation Dynamics

First, partial correlation analysis was conducted between both climatic and anthropogenic driving factors and GSNDVI at a county resolution to assess the interaction effects of individual environment drivers on grassland dynamics while controlling for other factors. In addition, to separate the relative contribution of each driving factor, the fraction in variation partitioning of the multiple standardized regression was applied. The outputs are the variations explained exclusively by each factor, the variations explained by the overlapping effects of each pair of factors, and the amount explained by the overlapping effects of all the explanatory factors. The amount of variations not explained by the complete model was also provided.

$$\frac{GSNDVI - \overline{GSNDVI}}{\sigma_{GSNDVI}} = \beta_0 + \beta_1 \frac{ED_1 - \overline{ED_1}}{\sigma_1} + \beta_n \frac{ED_n - \overline{ED_n}}{\sigma_n} \tag{6}$$

where ED_i (i = 1, 2, . . . , n) are environmental drivers, including GSP, GST and LI; $\overline{GSNDVI}$ and $\overline{ED_i}$ are inter-annual mean values of $GSNDVI$ and environmental drivers, respectively; and σ_{GSNDVI} and σ_i are standard deviations of $GSNDVI$ and climatic drivers, respectively. Each time series was normalized by subtracting its mean value and then dividing by its standard deviation. Thus any unit change in each variable has the same statistical meaning. Previous studies have shown that the regression coefficients β_i can reflect the relative effect or contribution of each climate driver to $GSNDVI$ and can be compared directly for the independent variables. With the above multi-regression, driving factors with larger standard regression coefficients can be assumed to contribute more to the variation of $GSNDVI$, and hence identified as the dominant driving factor with respect to the $GSNDVI$ variation.

2.3.3. Model Simulation Analysis

Similar to NDVI, Net Primary Productivity (NPP) is also an effective indicator of vegetation growth condition. The Terrestrial Ecosystem Model (TEM) was used to simulate the climatic Potential Net Primary Productivity (NPP_P) [44], which represents the maximum ecosystem NPP under certain climatic conditions and can be assumed to be driven solely by climatic factors. The Carnegie–Ames–Stanford Approach (CASA) model was used to simulate actual NPP (NPP_A), which is the actually occurring NPP. The NPP_A can be assumed to be influenced by both climatic factors and human activities. Thus, the human-induced NPP (NPP_H) affected exclusively by human activities can be simulated as follows:

$$NPP_H = NPP_P - NPP_A \tag{7}$$

$$NPP_P = a \times NPP_A + b \text{ Contribution} = \text{adjusted} - R^2 \tag{8}$$

We used the Equation (6) to obtain the spatial pattern of NPP and its two components [44]. Then, the total amount for each component was calculated for each county, and the contributions of climatic and anthropogenic factors were calculated via Equation (8). The adjusted$-R^2$ is the contribution of climate to vegetation vigor and $1-R^2$ is the unexplained variation possibly caused by human activities, including grazing. If the R^2 is greater than 0.5, then climate drivers are regarded as the dominant driving factor and vice versa. The result of the ecosystem productivity model was comparable to the contribution value from the statistical model's result derived from the Equation (6) at the county level.

The entire analysis was accomplished using the IDL8.3 of ENVI [45] and ArcGIS 10.1 (ESRI, Redlands, CA, USA, 2012).

3. Results

3.1. Variation in Enviromental Variables and Vegetation Vigor Dynamics

Figure 2 shows that the GSP over the whole QTP did not exhibit significant trends or any trend change. The *uf(t)* and *ub(t)* curves for GST intersected three times between 1993 and 2000. All of the intersection points were statistically significant (exceeding the confidence level of 95%). Then, the entire plateau was separated into Tibet and Qinghai, for which some trend change points for temperature and precipitation can be identified. Over the period 1986–2011 in Tibet, the *uf(t)* and *ub(t)* curves intersected in 1998 for GSP and three times between 1994 and 1998 for GST during 1986–2011. All the intersected points were statistically significant. In contrast, for GSP in Qinghai, no significant trends or trend change points were identified. Points of intersection were just slightly below the confidence level of 95%. For GST in Qinghai, intersection points were also identified between 1995 and 1998. Thus, the year of 2000 was treated as the trend change point (year) for climate. To keep in line with climate driving factors, we separated the livestock grazing intensity time series into segments prior to and post 2000. For remote sensing NDVI data, we also separated GIMMS data into segments prior to and post 2000. MODIS data is available only after 2000. Thus, the separation point for remote sensing data is also in accord with that for the climate data.

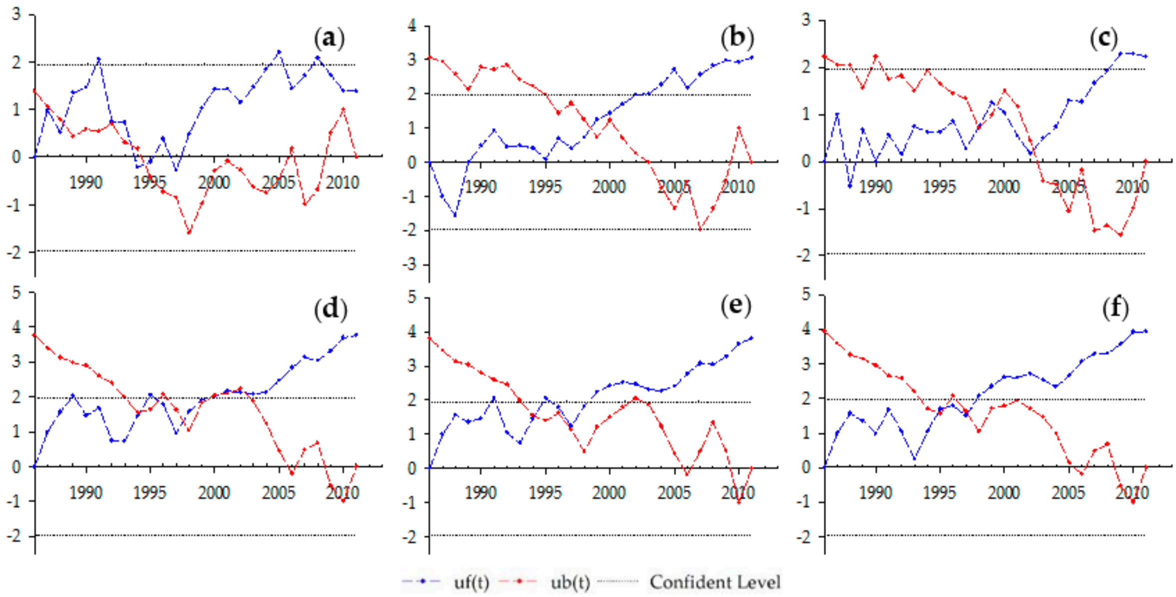


Figure 2. The sequential Mann-Kendall (SQ-MK) test to detect the trend shift points during 1986–2011 of (**a**) Growing season mean temperature (GST) for Qinghai-Tibet Plateau; (**b**) Growing season mean precipitation (GSP) for Tibet; (**c**) GSP for Qinghai; (**d**) GST for Qinghai-Tibet Plateau; (**e**) GST for Tibet; and (**f**) GST for Qinghai.

Averaged across grasslands for all counties, GST increased significantly (0.05 °C·year^{-1}, $p < 0.05$) for the entire plateau during 1986–2011. Across Tibet, the averaged inter-annual GST increased significantly ($p < 0.05$) for the periods of 1986–2000 (0.06 °C·year^{-1}) and 2000–2011 (0.04 °C·year^{-1}). For Qinghai, the GST increased significantly years both prior to 2000 (0.05 °C·year^{-1}) and afterwards (0.03 °C·year^{-1}). In contrast, the GSP exhibited a non-significant decreasing trend (−0.98 mm·year^{-1}) over the 26-year period for grasslands across the plateau. For the period of 1986–2000, the GSP exhibited insignificant trends in Qinghai and a significant increasing trend in Tibet (3.9 mm·year^{-1}). Then, from 2000 to 2011, GSP exhibited an increasing trend in Qinghai while displaying no significant change in Tibet. With respect to the stocking intensity, livestock numbers in Tibet have increased steadily since 1986 and shown a significant increasing trend from 2000 to 2011. In SJY, the livestock number showed a clear decreasing trend, especially after the Restoration of Grazing Project post 2000.

The vegetation vigor, as indicated by GSNDVI, exhibited increasing trends over the whole plateau for both the periods prior to and post 2000, as shown in Figure 3. Recalling that the entire 26-year period was divided into two segments at the year 2000, the GIMMS3g data showed that the increasing rate was 0.006/decade and 0.012/decade for the periods prior to and post 2000, respectively. After 2000, the MODIS data-based vegetation vigor exhibited an increasing rate of 0.0068/decade. Since GIMMS3g-derived GSNDVI showed an unreliable increase from 2008 to 2011 and MODIS GSNDVI did not, we only detect the county scale pattern of vegetation dynamics from 2000–2011 based on MODIS GSNDVI.

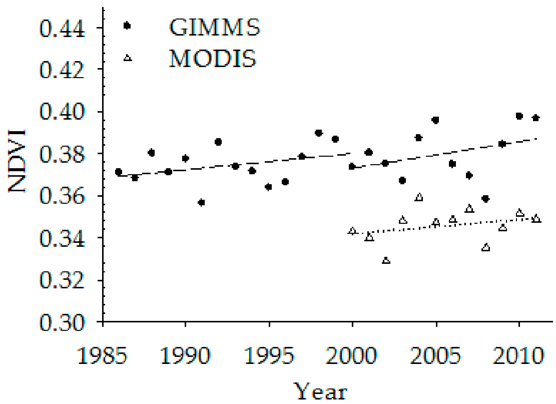


Figure 3. The trend of vegetation vigor in the Qinghai-Tibet Plateau during the period of 1986–2011, prior to 2000, and post 2000, GIMMS NDVI3g (Global Inventory Modeling and Mapping Studies Normalized Difference Vegetation Index) and MODIS NDVI (Moderate Resolution Imaging Spectro-radiometer Normalized Difference Vegetation Index).

For all counties across the plateau, GST showed steady increases during both periods. Thus, GST spatial patterns were not included in Figure 4. For vegetation vigor from 1986 to 2000, only six counties in the southern plateau showed a decreasing trend, while half of the counties in Tibet displayed a decreasing trend from 2000 to 2011. GSP over most counties in Qinghai decreased from 1986 to 2000, while the rest of the plateau experienced an increase in water supply from precipitation in the growing season. During 2000–2011, most counties in Tibet showed a decrease in GSP, the reverse was true for all counties in Qinghai. Prior to 2000, nearly all counties covered by alpine meadow in Tibet exhibited an increasing trend of grazing pressure, while counties in Sanjiangyuan showed a decreasing trend. Intensity of grazing also increased around the border of the Qiangtang Wildlife Sanctuary. The counties across the eastern part of the Qiangtang plateau even exhibited an increasing trend in grazing pressure after 2000.

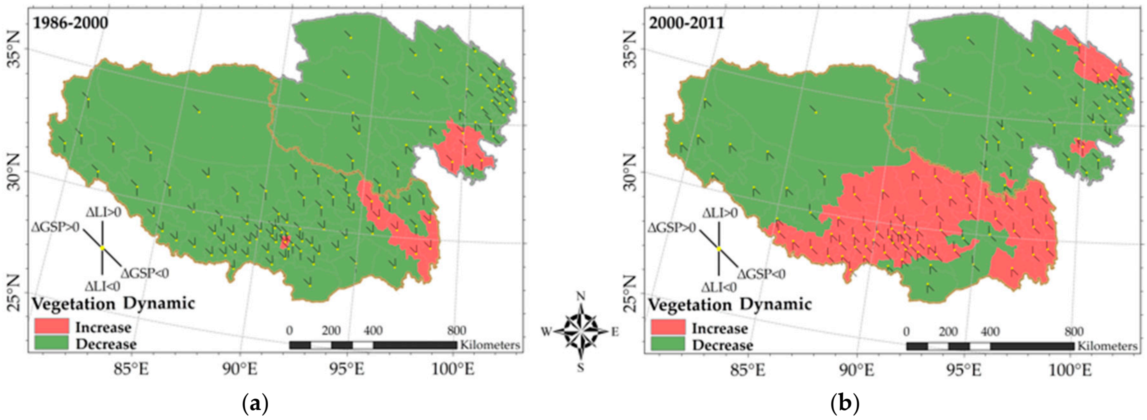


Figure 4. The change of Growing season mean precipitation (GSP), Livestock grazing intensity (LI) and vegetation vigor (based on growing season NDVI from Global Inventory Modeling and Mapping Studies Normalized Difference Vegetation Index (GIMMS3g) and Moderate Resolution Imaging Spectro-radiometer (MODIS)) over counties on the Qinghai-Tibet Plateau (Tibet and Sanjiangyuan for LI) during (**a**) the periods prior to 2000 and (**b**) the periods post 2000.

3.2. Relationship between NDVI and Individual Environmental Factors

Effects of climate and grazing intensity on vegetation vigor were evaluated for the period of 1986–2000 using GIMMS3g and for 2000–2011 using MODIS (See Figure 5). Over the two periods, GSNDVI was significantly correlated with precipitation in more than 70% of the plateau. In less than 20% of the grassland areas, GSNDVI was significantly and negatively correlated with temperature. The total area where each driving factor exerted significant effects on vegetation vigor differed between 1986–2000 and 2000–2011. Prior to 2000, the vegetation dynamic was positively correlated with GST and GSP for nearly 95% and 60% of the plateau, respectively. GST displayed a negative correlation with GSNDVI for less than 50% of the plateau during 1986–2000 and 2000–2011. LI exerted a greater negative effect on GSNDVI from 2000 to 2011 than during 1986–2000.

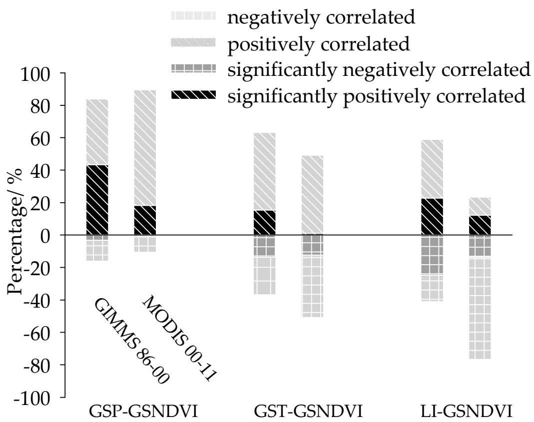


Figure 5. The percentage of pixels with positive and negative partial correlation coefficients indicating the determination of each environmental factor on the growing season NDVI (GSNDVI).

Variations in growing season NDVI over most counties of the plateau were positively correlated with GSP both prior to and after 2000. There were only a few counties situated on the wetter southern plateau whose grassland vegetation vigor showed an insignificant negative correlation with GSP (Figure 6a). During 2000–2011, the extremely dry counties around the Qiangtang Wildlife Sanctuary and the Qaidam Desert displayed insignificant negative correlation (Figure 6d). Grassland productivity is generally low in those counties where the correlation between GSP and vegetation was insignificant. In the arid alpine steppe area of the Qiangtang Plateau, vegetation vigor was positively and significantly correlated with GSP from 1986 to 2000. From 2000 to 2011, the semi-arid alpine meadow area in northeast plateau also displayed a positive correlation.

Vegetation dynamics of more than half of the counties over the entire plateau showed a positive correlation with GST (Figure 6b,e). For the arid Qiangtang Wildlife Sanctuary and the wet area of Qinghai, vegetation vigor was negatively correlated with GST before 2000. Then, from 2000 to 2011, the negative correlation was mainly distributed in the alpine meadow counties over the Tibet. Compared with climate factors, from 1986 to 2000, those counties whose vegetation dynamics showed a significant negative correlation with livestock intensity were distributed mainly in the alpine steppe region of the Qiangtang Plateau (Figure 6c). The counties across the arid alpine desert and steppe region show significant negative correlation of GST with vegetation vigor. GST in counties across the Qiangtang plateau showed a significant positive correlation with vegetation vigor just as GSP did. In most regions of the alpine meadow ecosystem, grazing intensity failed to show significant correlations with vegetation dynamics (Figure 6c,f).

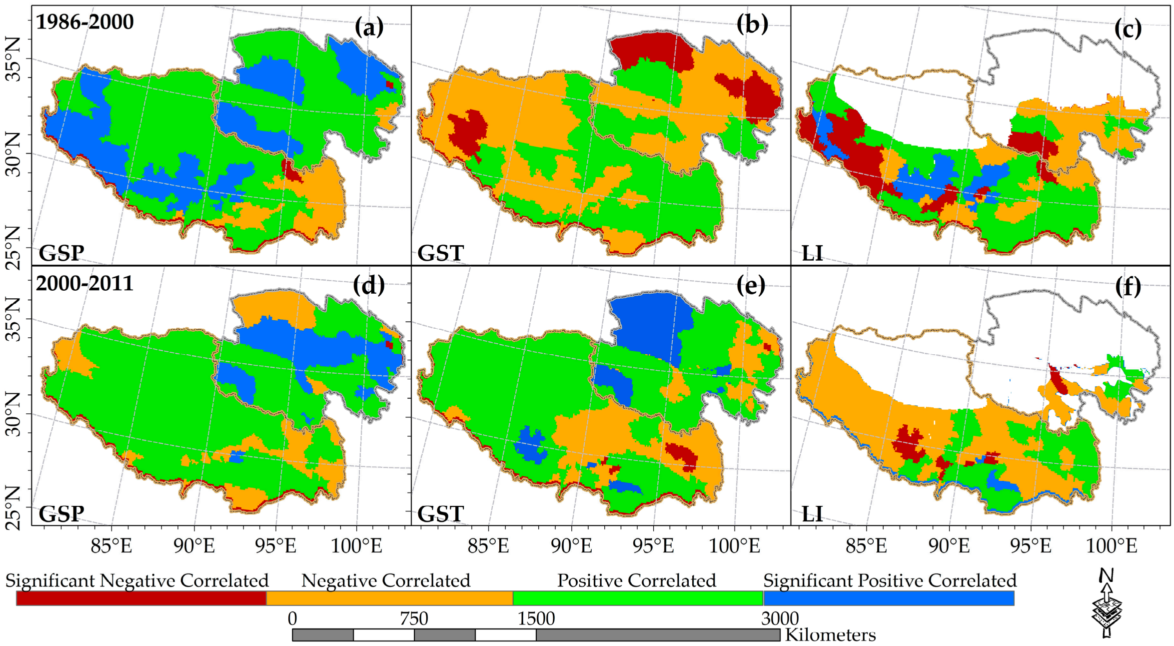


Figure 6. The correlation coefficients for: (**a**) The growing season precipitation (GSP) and the growing season NDVI (GSNDVI) for 1986–2000; (**b**) The growing season temperature (GST) and GSNDVI for 1986–2000; (**c**) Livestock grazing intensity (LI) and GSNDVI for 1986–2000; (**d**) GSP and GSNDVI for 2000–2011; (**e**) GST and GSNDVI for 2000–2011; and (**f**) LI and GSNDVI for 2000–2011.

3.3. The Climatic and Anthropogenic Contribution to Vegetation Vigor

Similar to results of the partial correlation coefficients, the spatial patterns of the dominant driving factors clearly differed between the periods prior to and post 2000. From 1986 to 2000 (Figure 7a), dynamics of grassland vegetation over all counties in QTP were driven primarily by precipitation. Increased precipitation favored vegetation vigor in the alpine steppe more than that in the arid region and the alpine meadow, except for the southern plateau and Sanjiangyuan. Increased precipitation and temperature provided a more favorable environment for alpine meadows across the South plateau and Qinghai. For the semi-arid ecosystem in the southern plateau and Sanjiangyuan, increased temperature was dominant. There are mainly three limited regions where grazing exerted great effects on vegetation dynamics: the alpine steppe around the border of the Qiangtang Wildlife Sanctuary, the southern plateau, and the Sanjiangyuan. With respect to the alpine steppe, where grazing intensity is mainly at a low or medium level, decreased grazing intensity around the border of the Qiangtang Wildlife Sanctuary tended to favor growth of grasslands in these counties (Figures A1a and 7a). For counties across the Sanjiangyuan and southern plateau in which grazing intensity is low or medium, warming and wetter climate improved vegetation growth maintaining the higher livestock carrying capacity of the alpine meadow (Figures A1a and 7a). For counties with high and extremely high grazing intensity, decreasing grazing intensity still exerted a negative impact on the vegetation after severe grazing disturbance (Figures A1a and 7a).

The dominant factors also displayed different patterns during 2000–2011 as compared with 1986–2000 (Figure 7b). As such, 81.6% of the areas in counties with declining vegetation vigor was mainly influenced by temperature or grazing. Meanwhile, precipitation exerted a greater impact on alpine meadows in Qinghai and the Qiangtang Wildlife Sanctuary. In the latter and on the southern edge of southwest plateau where the Himalaya Mountains intrude, precipitation still played a major role in vegetation dynamics. In the south plateau and Qiangtang plateau, temperatures acted as the dominant factor over a much larger area than during 1986–2000. Across the whole Qinghai-Tibet Plateau, the number of counties where grazing had been the dominant factor shrunk from that for the period prior to 2000. All of the counties that experienced enhanced vegetation, driven by the dominant factor of grazing, were found to also experience on average a high or medium decrease in grazing pressure from 2000 to 2011 (Figures A1a and 7b).

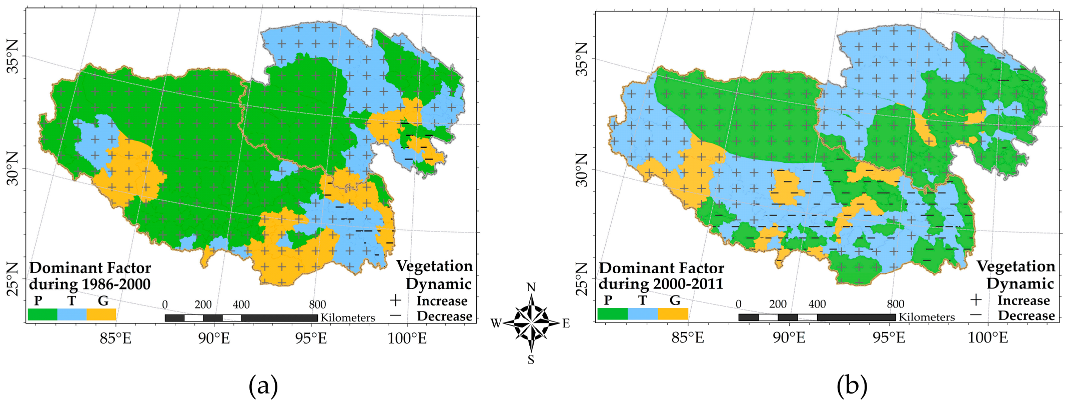


Figure 7. The dominant factors—the growing season temperature GST (T), the growing season precipitation GSP (P), and livestock grazing intensity LI (G)—driving variation in vegetation vigor across the Qinghai-Tibet Plateau during (**a**) the periods prior to 2000 and (**b**) the periods post 2000. The "+" indicates areas of decreasing trend in vegetation vigor; while the "−" represents areas of declining vegetation vigor.

3.4. Comparison of Statistical Results and Productivity Model Results

The statistical regression model using data from annual records indicated that in most of grasslands in the QTP—82.3% from 1986 to 2000 and 90.6% from 2000 to 2011—vegetation dynamics were driven by climate (Figure 8a,b). The regression model and the process model, as well as the remote sensing model showed that the region dominated by anthropogenic activity comprised less than 15.7% and 39.5% of the vegetated land prior to and post 2000, respectively. Areas in this region as detected by the regression model were smaller and more dispersed than those identified in the ecosystem productivity model. During 2000–2011, these latter areas were found mainly in counties inside Tibet along the Qinghai-Tibet Railway (Figure 8d). This was not revealed by a statistical model since this kind of anthropogenic activity was not recorded in the livestock yearbook. Furthermore, in the ecosystem productivity model, the relationships were first calculated by each pixel, while in the statistical model the analysis was conducted by each county. These scale differences are likely the main cause of these spatial inconsistencies. The two methods both revealed that the total area of climate-dominated grasslands was far larger than that dominated by anthropogenic activities.

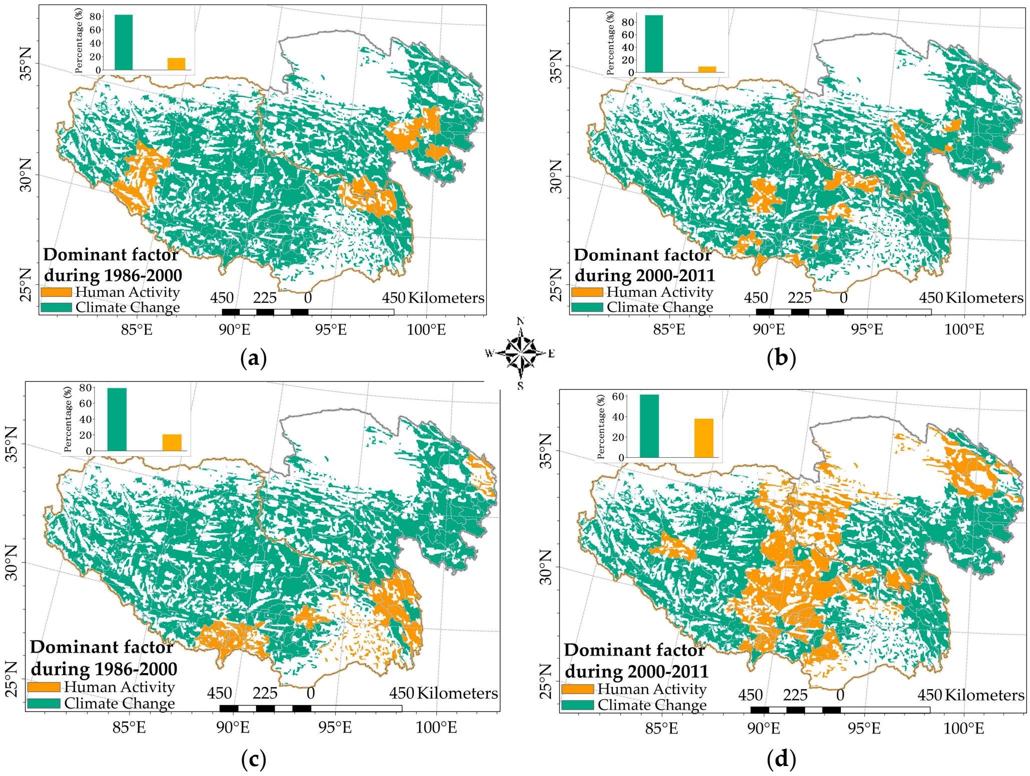


Figure 8. The dominant factors driving the dynamics of vegetation vigor across Qinghai-Tibet Plateau (**a**,**b**): Dominant driving factors during 1986–2000 and 2000–2011 as identified from statistical model; (**c**,**d**): Dominant driving factors during 1986–2000 and 2000–2011 with higher variation explained via ecosystem production model. Bar charts in upper-left corner show the percentage of total area impacted by driving factors. Note: Contribution of climate change in (**a**,**b**) to vegetation vigor = $\sum$ GST + GSP contributions.

4. Discussion

The significant warming and non-significant precipitation trends across the Qinghai-Tibet Plateau as identified in this study were in accord with findings of previous studies [46,47]. However, pronounced shifts in the temporal climate trend occurred around the year 2000. Geographically, Tibet and Qinghai are characterized by different thermal heating systems and separate water vapor sources [48,49]. The higher elevation of Tibet than Qinghai can lead to more rapid temperature increases in Tibet. In addition, more dense vegetation in Qinghai relative to that in Tibet can cause stronger evapotranspiration, thereby attenuating surface warming by altering the surface latent heat flux and sensible heat flux [50,51]. Furthermore, there is a higher percentage of glacial and lake surface area in Tibet than in Qinghai [52]. Under a warming climate, changes in glacier and snow cover altered the proportion of received shortwave radiation (surface albedo) and outgoing longwave radiation (surface emissivity), leading to a greater rate of warming in Tibet than in Qinghai [53–56]. The spatial pattern of precipitation change is much more complicated than that of temperature. The precipitable water in the atmosphere has been shown to have increased significantly since the 1990s due to increased atmospheric moisture from melting glaciers in Tibet [57]. Across the Qiangtang plateau and southeast plateau, summer rainfall is controlled mainly by "up-and-over" moisture transport, which is deep convection over the Indian subcontinent [58]. Increased aerosol accumulation over northern India will warm and dry the upper troposphere over the QTP, and strongly modulate ENSO influence [59,60], ultimately leading to a decline in growing season precipitation in the Qiangtang and southeast plateaus.

Under duel pressure from the ongoing changing climate and social-economic development, the Chinese government has taken various measures to tune the local economy and industry in the direction of sustainable development [61]. Relatively, the economic structure in Tibet is simpler than in Qinghai, resulting in a greater dependency on husbandry in Tibet. Due to the rapid husbandry development of Tibet, over the last three decades, total livestock numbers increased faster in Tibet than in Qinghai. Sanjiangyuan, the home to 300,000 Tibetan pastoralists, encompasses the headwaters of the Yangtze, Yellow and Mekong Rivers. The fundamental environmental and ecological significance of Sanjiangyuan to China underscores the mounting efforts being paid in every aspect, and Sanjiangyuan is one of the best-protected natural reserves in China [62]. All these efforts have obviously slowed the growth rate of livestock numbers in Qinghai. Reduced grazing intensity can lead to a series of positive environmental consequences, such as reducing compaction of surface soil and improving soil water retention and hydraulic conductivity [63].

Both climate change and anthropogenic activity could have a non-negligible influence on vegetation growth [64,65]. Consistent with trends of climatic and human activity-related factors, the vigor of grassland vegetation across the plateau displayed different trends for the periods prior to and post 2000. During the last decade of the 20th century, an increase in vegetation vigor occurred across almost all of the plateau. After 2000, the decline in vegetation vigor was detected mainly across the previously highly productive high-cold steppe and meadows of the Qiangtang and south plateaus [66–68], which are the primary fodder-providing regions. This shift created huge challenges for husbandry development in these regions.

For ecosystems other than grasslands, including forests and agricultural lands, effects of human activities are various and complex and thereby hard to quantify. Normally, contributions of human activities to variations in vegetation were calculated from the residuals of the NDVI-soil moisture or NDVI-rainfall regression models by applying residual trend analysis (RESTREND) [69,70]. However, the RESTREND can only quantify effects stemming from climatic variables. The Qinghai-Tibet Plateau represents a unique system, where intensity of human interference is quite low and pasture has been a traditional landscape for over a thousand years long [71]. Grazing is the primary type of human activity on the plateau, which provides a rare opportunity to simplify the process of quantifying effects of anthropogenic activity.

Similar to previous studies, we found that vegetation was greatly affected by precipitation [72,73]. Temperature clearly led to a decline in vegetation vigor in Tibet during the hotter years and in drier regions, which is consistent with the findings of other similar studies [66,74]. The spatially-varied dominant effects caused by precipitation and temperature embody the heterogeneous climate sensitivity on the plateau under different climatic conditions [75]. Temperature is the main limiting factor under conditions of adequate moisture in areas such as alpine meadows in Qinghai and across the warming meadows in Tibet. Increasing precipitation benefits vegetation growth by providing a sufficient water supply under a continually warming climate and throughout water-limited ecosystems, which has also been confirmed along grassland transects in Inner Mongolia [76]. In addition to the direct precipitation from the atmosphere, permafrost soils and melting of snow at high elevations could also serve as an indirectly supply of water. These effects might counterbalance the decline in precipitation at the southwestern border of the Qiangtang Wildlife Sanctuary.

Providing food and habitat for livestock is a vital ecosystem service of grasslands. Traditionally, for the rangeland contracted to individual pastoralists, pastoral residents have tended to maximize their livestock numbers during years of favorable climate and abundance of grassland forage [77]. However, the local nomads are not willing to decrease their livestock herds even under situations when fodder is scarce [78]. As a result, enhanced livestock intensity, along with increasing temperatures and slightly decreasing precipitation, has clearly resulted in an alarming reduction of vegetation vigor in some regions of Tibet. Impacted vegetation can change the energy balance [79] and moisture conditions [80] on the plateau, which will in turn impact soil and its capacity for water conservation; hence, the "Asian water tower" and "ecological hurdle" functions of the Tibetan Plateau.

In contrast to the results of some studies conducted at a local scale [81], this study identified greater effects on vegetation vigor from climate than from grazing. Findings consistent with ours have been suggested in studies of other similar ecosystems [41,82] and research on mechanisms underlying the scope of climatic driving forces [83]. Also, in our research, the decreased grazing pressure can benefit the restoration of grassland in the alpine desert region and regions where grazing pressure is not severe, which is also reflected in Wang's research at a finer spatial resolution [84]. In the long run, climate inevitably causes impacts on the vigor of grassland vegetation in the Qinghai-Tibet Plateau, just as it impacted the greenness of the Sahel during the years following the drought in the 1980s [85–87]. Moderate utilization of pasture by humans affects vegetation vigor in the short run. Corresponding measures may be suggested to be taken by both local governments and herdsman grounded in a thorough understanding of their combined effects and respective contributions. Such knowledge is critical to achieving sustainable management of the pastoral ecosystems of the Qinghai-Tibet Plateau.

The accuracy of this study is constrained by the fact that spatially explicit data on grazing intensity at a regional scale in terms of grazing locations and grazing period is not available. Currently, data from annual records is provided county by county. In the future, more comprehensive and spatially explicit survey data and remote sensing data at finer spatial resolutions are needed to enhance research capabilities. With more refined datasets on enclosures (i.e., fencing) and artificial grassland dataset, we can conduct further research on the lagging effects of grazing on the recovery of grasslands, in particular geographic regions.

Another limitation of the study is that the relationships between vegetation dynamics and potential driving forces have been quantified, but the quantified relationship cannot be directly used to represent underlying causal relationships. Also, there might be lagged effects caused by overgrazing. The underlying mechanisms need to be further explored using a comprehensive model that can incorporate most of the relevant factors [83].

5. Conclusions

(1) On an overall basis, the grassland ecosystems of the Qinghai Plateau have experienced a climate that is clearly changing along with varying intensities of grazing disturbance. Regions where climate has played a dominant role in affecting vegetation growth are much larger than those similarly affected by grazing, which demonstrates that grassland on the Qinghai-Tibet is a climate-driven system.

(2) Prior to and following the year 2000, the climate conditions on the Qinghai-Tibet Plateau displayed different trends. From 1986 to 2000, a wetter and warmer climate improved grassland growth through most of the Plateau. From 2000 to 2011, the drier and hotter climate disfavored grassland growth, especially in the arid regions across Tibet.

(3) Under favorable climate conditions, grassland ecosystems such as the alpine meadow in the Qinghai-Tibet Plateau can sustain the traditional grazing intensity. Under the harsher climate conditions, government and herders themselves did not manage and lighten the grazing intensity, causing a decline and even degradation of grassland vegetation.

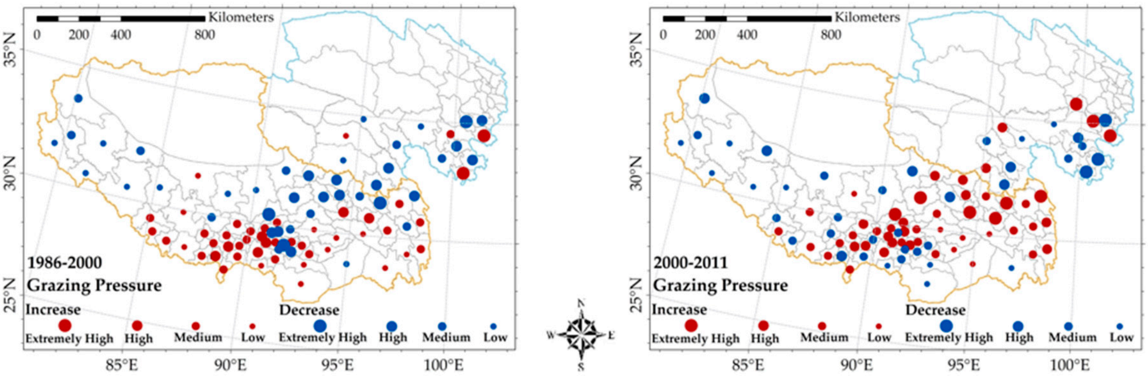
Acknowledgments: This research was funded by the following projects: the Chinese National Key Program for Developing Basic Science (2013CB956302), and the Science and Technology Project of the Chinese Academy of Sciences (XDA05050400). We thank Jian Tao, Tao Zhang and Jyoti Bhandari for their valuable comments and suggestions. We also thank the journal editor and the anonymous reviewers for their useful comments and efforts on this paper.

Author Contributions: Ke Huang, Yangjian Zhang and Juntao Zhu designed the study. Ke Huang was responsible for the data processing and analysis. Ke Huang and Yangjian Zhang wrote this paper. Yaojie Liu, Jiaxing Zu, Jing Zhang provided valuable suggestions about the revision.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Figure A1 illustrated the spatial pattern of the grazing pressure over the Qinghai-Tibet Plateau prior to 2000 and post 2000. The grazing pressure is the livestock number (sheep equivalent unit number, SUN) per grassland area for a particular year. The high grazing pressure was mainly distributed on alpine meadows of the Qiangtang Plateau and southern Tibet and Sanjiangyuan. During 1986–2000, the grazing pressure showed a continuous increasing trend mainly over the Southwest Plateau and the South Plateau, where the grazing pressure was at a high level (Figure A1a). Meanwhile, the grazing pressure in the extremely high grazing pressure counties of Qiangtang Pleateau showed a continuous decreasing trend. In Sanjiangyuan, the grazing pressure mostly was decreasing. During 2000–2011, most of the high and extremely high grazing pressure counties showed an upward trend over southwest plateau, south plateau and Qiangtang Plateau (Figure A1b). In Sanjiangyuan, half of the extremely high grazing pressure counties showed an upward trend. Some other studies found that climate is the principal driving force for grassland degradation, whereas human activities are the dominant factor in grassland restoration [84].



(**a**) (**b**)

Figure A1. The multi-year average grazing pressure and the temporal trend (**a**) During 1986–2000; (**b**) During 2000–2011 at a county scale.

References

1. Sun, H.L.; Zheng, D. *Formation and evolution of Qinghai-Xizang Plateau*; Shanghai Science and Technology Press: Shanghai, China, 1996; Volume 1. (In Chinese)
2. Genxu, W.; Ju, Q.; Guodong, C.; Yuanmin, L. Soil organic carbon pool of grassland soils on the Qinghai-Tibetan Plateau and its global implication. *Sci. Total Environ.* **2002**, *291*, 207–217. [CrossRef]
3. Wang, Y.J.; Cheng, H.; Edwards, R.L.; An, Z.S.; Wu, J.Y.; Shen, C.C.; Dorale, J.A. A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China. *Science* **2001**, *294*, 2345–2348. [CrossRef] [PubMed]
4. Tan, K.; Ciais, P.; Piao, S.L.; Wu, X.P.; Tang, Y.H.; Vuichard, N.; Liang, S.; Fang, J.Y. Application of the ORCHIDEE global vegetation model to evaluate biomass and soil carbon stocks of Qinghai-Tibetan grasslands. *Glob. Biogeochem. Cycles* **2010**, *24*, GB1013. [CrossRef]
5. Yao, T.; Wu, F.; Ding, L.; Sun, J.; Zhu, L.; Piao, S.L.; Deng, T.; Ni, X.; Zheng, H.; Ouyang, H. Multispherical interactions and their effects on the Tibetan Plateau's earth system: A review of the recent researches. *Natl. Sci. Rev.* **2015**, *2*, 468–488. [CrossRef]
6. Thompson, D.W.; Solomon, S. Interpretation of recent southern Hemisphere climate change. *Science* **2002**, *296*, 895–899. [CrossRef] [PubMed]
7. Piao, S.; Ciais, P.; Huang, Y.; Shen, Z.; Peng, S.; Li, J.; Zhou, L.; Liu, H.; Ma, Y.; Ding, Y.; et al. The impacts of climate change on water resources and agriculture in China. *Nature* **2010**, *467*, 43–51. [CrossRef] [PubMed]

8. Graven, H.D.; Keeling, R.F.; Piper, S.C.; Patra, P.K.; Stephens, B.B.; Wofsy, S.C.; Welp, L.R.; Sweeney, C.; Tans, P.P.; Kelley, J.J.; et al. Enhanced seasonal exchange of CO_2 by northern ecosystems since 1960. *Science* **2013**, *341*, 1085–1089. [CrossRef] [PubMed]
9. Pepin, N.; Bradley, R.S.; Diaz, H.F.; Baraer, M.; Caceres, E.B.; Forsythe, N.; Fowler, H.; Greenwood, G.; Hashmi, M.Z.; Liu, X.D.; et al. Elevation-dependent warming in mountain regions of the world. *Nat. Clim. Chang.* **2015**, *5*, 424–430. [CrossRef]
10. Liu, X.; Yin, Z.-Y.; Shao, X.; Qin, N. Temporal trends and variability of daily maximum and minimum, extreme temperature events, and growing season length over the eastern and central Tibetan Plateau during 1961–2003. *J. Geophys. Res.* **2006**, *111*, D19109. [CrossRef]
11. You, Q.; Kang, S.; Aguilar, E.; Yan, Y. Changes in daily climate extremes in the eastern and central Tibetan Plateau during 1961–2005. *J. Geophys. Res.* **2008**, *113*, D07101. [CrossRef]
12. Gao, Q.Z.; Wan, Y.F.; Li, Y.; Qin, X.B.; Jiangcun, W.; Xu, H.M. Spatial and temporal pattern of alpine grassland condition and its response to human activities in Northern Tibet, China. *Rangel. J.* **2010**, *32*, 165–173. [CrossRef]
13. Tucker, C.J.; Sellers, P.J. Satellite remote sensing of primary production. *Int. J. Remote Sens.* **1986**, *7*, 1395–1416. [CrossRef]
14. De Jong, R.; de Bruin, S.; de Wit, A.; Schaepman, M.E.; Dent, D.L. Analysis of monotonic greening and browning trends from global NDVI time-series. *Remote Sens. Environ.* **2011**, *115*, 692–702. [CrossRef]
15. Tian, F.; Brandt, M.; Liu, Y.Y.; Verger, A.; Tagesson, T.; Diouf, A.A.; Rasmussen, K.; Mbow, C.; Wang, Y.J.; Fensholt, R. Remote sensing of vegetation dynamics in drylands: Evaluating vegetation optical depth (VOD) using AVHRR NDVI and in situ green biomass data over West African Sahel. *Remote Sens. Environ.* **2016**, *177*, 265–276. [CrossRef]
16. Pinzon, J.; Tucker, C. A non-stationary 1981–2012AVHRR NDVI3g time series. *Remote Sens.* **2014**, *6*, 6929–6960. [CrossRef]
17. Zhu, Z.C.; Bi, J.; Pan, Y.Z.; Ganguly, S.; Anav, A.; Xu, L.; Samanta, A.; Piao, S.L.; Nemani, R.R.; Myneni, R.B. Global data sets of vegetation leaf area index (LAI)3g and fraction of photosynthetically active radiation (FPAR)3g derived from global inventory modeling and mapping studies (GIMMS) normalized difference vegetation index (NDVI3g) for the period 1981 to 2011. *Remote Sens.* **2013**, *5*, 927–948.
18. Ibrahim, Y.Z.; Balzter, H.; Kaduk, J.; Tucker, C.J. Land degradation assessment using residual trend analysis of GIMMS NDVI3g, soil moisture and rainfall in Sub-Saharan West Africa from 1982 to 2012. *Remote Sens.* **2015**, *7*, 5471–5494. [CrossRef]
19. Brown, M.E.; Pinzon, J.E.; Didan, K.; Morisette, J.T.; Tucker, C.J. Evaluation of the consistency of long-term NDVI time series derived from AVHRR, SPOT-Vegetation, SeaWIFS, MODIS, and Landsat ETM+ sensors. *IEEE Trans. Geosci. Remote* **2006**, *44*, 1787–1793. [CrossRef]
20. Tian, F.; Fensholt, R.; Verbesselt, J.; Grogan, K.; Horion, S.; Wang, Y.J. Evaluating temporal consistency of long-term global NDVI datasets for trend analysis. *Remote Sens. Environ.* **2015**, *163*, 326–340. [CrossRef]
21. Zhang, G.L.; Zhang, Y.J.; Dong, J.W.; Xiao, X.M. Green-up dates in the Tibetan Plateau have continuously advanced from 1982 to 2011. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 4309–4314. [CrossRef] [PubMed]
22. Fensholt, R.; Proud, S.R. Evaluation of earth observation based global long term vegetation trends—Comparing GIMMS and MODIS global NDVI time series. *Remote Sens. Environ.* **2012**, *119*, 131–147. [CrossRef]
23. Tasumi, M.; Hirakawa, K.; Hasegawa, N.; Nishiwaki, A.; Kimura, R. Application of MODIS land products to assessment of land degradation of alpine rangeland in northern India with limited ground-based information. *Remote Sens.* **2014**, *6*, 9260–9276. [CrossRef]
24. Li, Z.Q.; Guo, X.L. Detecting climate effects on vegetation in northern mixed prairie using NOAA AVHRR 1-km time-series NDVI data. *Remote Sens.* **2012**, *4*, 120–134. [CrossRef]
25. Wang, C.; Guo, H.; Zhang, L.; Liu, S.; Qiu, Y.; Sun, Z. Assessing phenological change and climatic control of alpine grasslands in the Tibetan Plateau with MODIS time series. *Int. J. Biometeorol.* **2015**, *59*, 11–23. [CrossRef] [PubMed]
26. Zhang, J.H.; Yao, F.M.; Zheng, L.G.; Yang, L.M. Evaluation of grassland dynamics in the Northern-Tibet Plateau of China using remote sensing and climate data. *Sensors* **2007**, *7*, 3312–3328. [CrossRef]
27. Peng, J.; Liu, Z.; Liu, Y.; Wu, J.; Han, Y. Trend analysis of vegetation dynamics in Qinghai–Tibet Plateau using Hurst Exponent. *Ecol. Indic.* **2012**, *14*, 28–39. [CrossRef]

28. Ding, M.; Zhang, Y.; Liu, L.; Zhang, W.; Wang, Z.; Bai, W. The relationship between NDVI and precipitation on the Tibetan Plateau. *J. Geogr. Sci.* **2007**, *17*, 259–268. [CrossRef]
29. Zhang, Y.; Gao, J.; Liu, L.; Wang, Z.; Ding, M.; Yang, X. NDVI-based vegetation changes and their responses to climate change from 1982 to 2011: A case study in the Koshi River Basin in the middle Himalayas. *Glob. Planet. Chang.* **2013**, *108*, 139–148. [CrossRef]
30. Huang, C.; Li, Y.; Liu, G.; Zhang, H.; Liu, Q. Recent climate variability and its impact on precipitation, temperature, and vegetation dynamics in the Lancang River headwater area of China. *Int. J. Remote Sens.* **2014**, *35*, 2822–2834. [CrossRef]
31. Sun, J.; Qin, X.; Yang, J. The response of vegetation dynamics of the different alpine grassland types to temperature and precipitation on the Tibetan Plateau. *Environ. Monit. Assess.* **2016**, *188*, 20. [CrossRef] [PubMed]
32. Li, X.L.; Gao, J.; Brierley, G.; Qiao, Y.M.; Zhang, J.; Yang, Y.W. Rangeland degradation on the Qinghai-Tibet Plateau: Implications for rehabilitation. *Land Degrad. Dev.* **2013**, *24*, 72–80. [CrossRef]
33. Zhang, T.; Zhang, Y.; Xu, M.; Zhu, J.; Wimberly, M.C.; Yu, G.; Niu, S.; Xi, Y.; Zhang, X.; Wang, J. Light-intensity grazing improves alpine meadow productivity and adaption to climate change on the Tibetan Plateau. *Sci. Rep.* **2015**, *5*, 15949. [CrossRef] [PubMed]
34. Zheng, D. The system of physico-geographical regions of the Qinghai-Xizang (Tibet) Plateau. *Sci. China Ser. D* **1996**, *39*, 410–417.
35. Fu, Q.; Zhu, Y.Q.; Kong, Y.F.; Sun, J.L. Spatial analysis and districting of the livestock and poultry breeding in China. *J. Geogr. Sci.* **2012**, *22*, 1079–1100. [CrossRef]
36. China Meteorological Center. Available online: http://data.cma.cn/site/index.html (accessed on 27 May 2016).
37. Hutchinson, M.F.; Xu, T.B. *Anusplin Version 4.4 User Guide*; The Australian National University: Canberra, Australia, 2013.
38. Ecological Forecasting Lab at NASA Ames Research Center (ECOCAST). Available online: http://ecocast.arc.nasa.gov/data/pub/gimms/3g.v0/ (accessed on 27 May 2016).
39. Atmosphere Archive and Distribution System (LAADS) Web. Level 1 and Atmosphere Archive and Distribution System. Available online: http://ladsweb.nascom.nasa.gov/data/ (access on 31 May 2016).
40. Qian, S.; Mao, L.X.; Hou, Y.Y.; Fu, Y.; Zhang, H.Z.; Du, J. Livestock carrying capacity and balance between carrying capacity of grassland with added forage and actual livestock in the Qinghai-Tibet Plateau. *J. Natl. Res.* **2007**, *22*, 389–396.
41. Lehnert, L.W.; Wesche, K.; Trachte, K.; Reudenbach, C.; Bendix, J. Climate variability rather than overstocking causes recent large scale cover changes of Tibetan pastures. *Sci. Rep.* **2016**, *6*, 24367. [CrossRef] [PubMed]
42. Sneyers, R. *On the Statistical Analysis of Series of Observations*; Secretariat of the World Meteorological Organization: Geneva, Switzerland, 1990.
43. Sayemuzzaman, M.; Jha, M.K. Seasonal and annual precipitation time series trend analysis in North Carolina, United States. *Atmos. Res.* **2014**, *137*, 183–194. [CrossRef]
44. Chen, B.X.; Zhang, X.Z.; Tao, J.; Wu, J.S.; Wang, J.S.; Shi, P.L.; Zhang, Y.J.; Yu, C.Q. The impact of climate change and anthropogenic activities on Alpine grassland over the Qinghai-Tibet Plateau. *Agric. For. Meteorol.* **2014**, *189*, 11–18. [CrossRef]
45. Canty, M.J. *Image Analysis, Classification and Change Detection in Remote Sensing: With Algorithms for ENVI/IDL and Python*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2014.
46. Tao, J.; Zhang, Y.J.; Dong, J.W.; Fu, Y.; Zhu, J.T.; Zhang, G.L.; Jiang, Y.B.; Tian, L.; Zhang, X.Z.; Zhang, T.; et al. Elevation-dependent relationships between climate change and grassland vegetation variation across the Qinghai-Xizang Plateau. *Int. J. Climatol.* **2015**, *35*, 1638–1647. [CrossRef]
47. Liu, J.S.; Wang, S.Y.; Yu, S.M.; Yang, D.Q.; Zhang, L. Climate warming and growth of high-elevation inland lakes on the Tibetan Plateau. *Glob. Planet. Chang.* **2009**, *67*, 209–217. [CrossRef]
48. Guo, X.; Yang, K.; Chen, Y. Weakening sensible heat source over the Tibetan Plateau revisited: Effects of the land–atmosphere thermal coupling. *Theor. Appl. Climatol.* **2011**, *104*, 1–12. [CrossRef]
49. Yang, K.; Wu, H.; Qin, J.; Lin, C.G.; Tang, W.J.; Chen, Y.Y. Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: A review. *Glob. Planet. Chang.* **2014**, *112*, 79–91. [CrossRef]
50. Zhang, X.; Tang, Q.; Zheng, J.; Ge, Q. Warming/cooling effects of cropland greenness changes during 1982–2006 in the North China Plain. *Environ. Res. Lett.* **2013**, *8*, 024038. [CrossRef]

51. Jeong, S.-J.; Ho, C.-H.; Kim, K.-Y.; Jeong, J.-H. Reduction of spring warming over East Asia associated with vegetation feedback. *Geophys. Res. Lett.* **2009**, *36*, L18705. [CrossRef]
52. Wan, W.; Long, D.; Hong, Y.; Ma, Y.; Yuan, Y.; Xiao, P.; Duan, H.; Han, Z.; Gu, X. A lake data set for the Tibetan Plateau from the 1960s, 2005, and 2014. *Sci. Data* **2016**, *3*, 160039. [CrossRef] [PubMed]
53. Kang, S.C.; Xu, Y.W.; You, Q.L.; Flugel, W.A.; Pepin, N.; Yao, T.D. Review of climate and cryospheric change in the Tibetan Plateau. *Environ. Res. Lett.* **2010**, *5*, 015101. [CrossRef]
54. Duan, A.M.; Wu, G.X. Role of the Tibetan Plateau thermal forcing in the summer climate patterns over subtropical Asia. *Clim. Dyn.* **2005**, *24*, 793–807. [CrossRef]
55. Duan, A.M.; Wu, G.X. Weakening trend in the atmospheric heat source over the Tibetan Plateau during recent decades. Part I: Observations. *J. Clim.* **2008**, *21*, 3149–3164. [CrossRef]
56. Duan, A.M.; Wu, G.X. Weakening trend in the atmospheric heat source over the Tibetan Plateau during recent decades. Part II: Connection with climate warming. *J. Clim.* **2009**, *22*, 4197–4212. [CrossRef]
57. Zhang, D.; Huang, J.; Guan, X.; Chen, B.; Zhang, L. Long-term trends of precipitable water and precipitation over the Tibetan Plateau derived from satellite and surface measurements. *J. Quant. Spectrosc. Radiat. Transf.* **2013**, *122*, 64–71. [CrossRef]
58. Dong, W.; Lin, Y.; Wright, J.S.; Ming, Y.; Xie, Y.; Wang, B.; Luo, Y.; Huang, W.; Huang, J.; Wang, L.; et al. Summer rainfall over the southwestern Tibetan Plateau controlled by deep convection over the Indian subcontinent. *Nat. Commun.* **2016**, *7*, 10925. [CrossRef] [PubMed]
59. Kim, M.-K.; Lau, W.K.M.; Kim, K.-M.; Sang, J.; Kim, Y.-H.; Lee, W.-S. Amplification of ENSO effects on Indian summer monsoon by absorbing aerosols. *Clim. Dyn.* **2015**, *46*, 2657–2671. [CrossRef]
60. Lau, K.M.; Kim, K.M. Observational relationships between aerosol and Asian monsoon rainfall, and circulation. *Geophys. Res. Lett.* **2006**, *33*, L21810. [CrossRef]
61. Zhao, G.H.; Tian, Y.; Tang, Z.Y.; Li, J.S.; Zeng, H. Distribution of terrestrial national nature reserves in relation to human activities and natural environments in China. *Biodivers. Sci.* **2013**, *21*, 658–665.
62. State Council of the People's Republic of China. *Ecological Protection and Construction of Qinghai Three Rivers Nature Reserve Master Plan*; State Council of the People's Republic of China: Beijing, China, 2005; p. 54. (In Chinese)
63. Zeng, C.; Zhang, F.; Wang, Q.; Chen, Y.; Joswiak, D.R. Impact of alpine meadow degradation on soil hydraulic properties over the Qinghai-Tibetan Plateau. *J. Hydrol.* **2013**, *478*, 148–156. [CrossRef]
64. Cai, D.; Fraedrich, K.; Sielmann, F.; Guan, Y.; Guo, S.; Zhang, L.; Zhu, X. Climate and vegetation: An ERA-interim and GIMMS NDVI analysis. *J. Clim.* **2014**, *27*, 5111–5118. [CrossRef]
65. Cui, X.; Graf, H.-F. Recent land cover changes on the Tibetan Plateau: A review. *Clim. Chang.* **2009**, *94*, 47–61. [CrossRef]
66. Gao, Q.; Guo, Y.; Xu, H.; Ganjurjav, H.; Li, Y.; Wan, Y.; Qin, X.; Ma, X.; Liu, S. Climate change and its impacts on vegetation distribution and net primary productivity of the alpine ecosystem in the Qinghai-Tibetan Plateau. *Sci. Total Environ.* **2016**, *554–555*, 34–41. [CrossRef] [PubMed]
67. Gao, Q.; Wan, Y.; Li, Y.; Guo, Y.; Ganjurjav; Qin, X.; Jiangcun, W.; Wang, B. Effects of topography and human activity on the net primary productivity (NPP) of alpine grassland in northern Tibet from 1981 to 2004. *Int. J. Remote Sens.* **2013**, *34*, 2057–2069. [CrossRef]
68. Gao, Q.Z.; Ganjurjav; Li, Y.; Wan, Y.F.; Zhang, W.N.; Borjigdai, A. Challenges in disentangling the influence of climatic and socio-economic factors on alpine grassland ecosystems in the source area of Asian major rivers. *Quat. Int.* **2013**, *304*, 126–132. [CrossRef]
69. Dardel, C.; Kergoat, L.; Hiernaux, P.; Grippa, M.; Mougin, E.; Ciais, P.; Nguyen, C.-C. Rain-use-efficiency: What it tells us about the conflicting Sahel greening and Sahelian paradox. *Remote Sens.* **2014**, *6*, 3446–3474. [CrossRef]
70. Fensholt, R.; Rasmussen, K. Analysis of trends in the Sahelian "rain-use efficiency" using GIMMS NDVI, RFE and GPCP rainfall data. *Remote Sens. Environ.* **2011**, *115*, 438–451. [CrossRef]
71. Long, R.J.; Ding, L.M.; Shang, Z.H.; Guo, X.H. The yak grazing system on the Qinghai-Tibetan Plateau and its status. *Rangel. J.* **2008**, *30*, 241–246. [CrossRef]
72. Yang, Y.H.; Piao, S.L. Variations in grassland vegetation cover in relation to climatic factors on the Tibetan Plateau. *J. Plant Ecol.* **2006**, *30*, 1–8.
73. Zhang, X.K.; Lu, X.Y.; Wang, X. Spatial-temporal NDVI variation of different alpine grassland classes and groups in northern Tibet from 2000 to 2013. *Mt. Res. Dev.* **2015**, *35*, 254–263. [CrossRef]

74. Gao, Q.Z.; Li, Y.; Wan, Y.F.; Qin, X.B.; Jiangcun, W.Z.; Liu, Y.H. Dynamics of alpine grassland NPP and its response to climate change in northern Tibet. *Clim. Chang.* **2009**, *97*, 515–528. [CrossRef]
75. Molnar, P.; Boos, W.R.; Battisti, D.S. Orographic controls on climate and paleoclimate of Asia: Thermal and mechanical roles for the Tibetan Plateau. *Annu. Rev. Earth Plant. Sci.* **2010**, *38*, 77–102. [CrossRef]
76. Bai, Y.; Han, X.; Wu, J.; Chen, Z.; Li, L. Ecosystem stability and compensatory effects in the Inner Mongolia grassland. *Nature* **2004**, *431*, 181–184. [CrossRef] [PubMed]
77. Yu, C.; Zhang, Y.; Claus, H.; Zeng, R.; Zhang, X.; Wang, J. Ecological and environmental issues faced by a developing Tibet. *Environ. Sci. Technol.* **2012**, *46*, 1979–1980. [CrossRef] [PubMed]
78. Yan, J.; Wu, Y.; Zhang, Y. Adaptation strategies to pasture degradation: Gap between government and local nomads in the eastern Tibetan Plateau. *J. Geogr. Sci.* **2011**, *21*, 1112–1122. [CrossRef]
79. Tian, L.; Zhang, Y.J.; Zhu, J.T. Decreased surface albedo driven by denser vegetation on the Tibetan Plateau. *Environ. Res. Lett.* **2014**, *9*, 104001. [CrossRef]
80. Xu, X.D.; Lu, C.G.; Shi, X.H.; Gao, S.T. World water tower: An atmospheric perspective. *Geophys. Res. Lett.* **2008**, *35*, L20815. [CrossRef]
81. Du, M. Mutual influence between human activities and climate change in the Tibetan Plateau during recent years. *Glob. Planet. Chang.* **2004**, *41*, 241–249. [CrossRef]
82. Klein, J.A.; Harte, J.; Zhao, X.Q. Experimental warming, not grazing, decreases rangeland quality on the Tibetan Plateau. *Ecol. Appl.* **2007**, *17*, 541–557. [CrossRef] [PubMed]
83. Cai, D.; Fraedrich, K.; Sielmann, F.; Zhang, L.; Zhu, X.; Guo, S.; Guan, Y. Vegetation dynamics on the Tibetan Plateau (1982–2006): An attribution by ecohydrological diagnostics. *J. Clim.* **2015**, *28*, 4576–4584. [CrossRef]
84. Wang, Z.; Zhang, Y.; Yang, Y.; Zhou, W.; Gang, C.; Zhang, Y.; Li, J.; An, R.; Wang, K.; Odeh, I.; et al. Quantitative assess the driving forces on the grassland degradation in the Qinghai–Tibet Plateau, in China. *Ecol. Inform.* **2016**, *33*, 32–44. [CrossRef]
85. Held, I.M.; Delworth, T.L.; Lu, J.; Findell, K.L.; Knutson, T.R. Simulation of Sahel drought in the 20th and 21st centuries. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 17891–17896. [CrossRef] [PubMed]
86. Brandt, M.; Mbow, C.; Diouf, A.A.; Verger, A.; Samimi, C.; Fensholt, R. Ground- and satellite-based evidence of the biophysical mechanisms behind the greening Sahel. *Glob. Chang. Biol.* **2015**, *21*, 1610–1620. [CrossRef] [PubMed]
87. Kaptue, A.T.; Prihodko, L.; Hanan, N.P. On regreening and degradation in Sahelian watersheds. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 12133–12138. [CrossRef] [PubMed]