remote sensing

Article

Evaluation of Reasonable Stocking Rate Based on the Relative Contribution of Climate Change and Grazing Activities to the Productivity of Alpine Grasslands in Qinghai Province

Li Zhao [1,†], Zhenhua Liu [1,†], Yueming Hu [2,3,4,*], Wu Zhou [1], Yiping Peng [1], Tao Ma [3,4], Luo Liu [1], Shihua Li [5], Liya Wang [6] and Xiaoyun Mao [1]

1 College of Natural Resources and Environment, South China Agricultural University, Guangzhou 510642, China; zhaoli@stu.scau.edu.cn (L.Z.); zhenhua@scau.edu.cn (Z.L.); wuzhou@stu.scau.edu.cn (W.Z.); pengyp@stu.scau.edu.cn (Y.P.); liuluo@scau.edu.cn (L.L.); xymao@scau.edu.cn (X.M.)
2 College of Tropical Crops, Hainan University, Haikou 570228, China
3 College of Agriculture and Animal Husbandry, Qinghai University, Xining 810016, China; 1989990003@qhu.edu.cn
4 South China Academy of Natural Resources Science and Technology, Guangzhou 510642, China
5 School of Resources and Environment, University of Electronic Science and Technology of China, Chengdu 611731, China; lishihua@uestc.edu.cn
6 Natural Resources Comprehensive Investigation and Monitoring Institute of Qinghai Province, Xining 810000, China; wt@stu.scau.edu.cn
* Correspondence: ymhu@scau.edu.cn; Tel.: +86-020-8528-8307
† These authors contributed equally to this work.

Abstract: An accurate assessment of the stocking rate is crucial for maintaining the stable function and the sustainable use of the alpine grassland ecosystem. A new scenario design method to evaluate the reasonable stocking rate is presented in the current work. First, climate change is quantified by potential net primary productivity (NPP_p) and measured by adopting the Zhou Guangsheng model, and the NPP generated by anthropogenic activities (NPP_h) is estimated by the distinction between NPP_p and actual NPP (NPP_a) calculated with the application of the Carnegie–Ames–Stanford Approach (CASA) model. Second, using the NPP_h and actual grassland productivity consumed by livestock (NPP_{ac}), the reasonable stocking rate is obtained. Finally, the driving factors of NPP change in alpine grassland and the reasonable stocking rate are clarified in Qinghai Province during 2005–2018. The results reveal that the temperature of alpine grassland in Qinghai Province has a slight upward trend from 2005 to 2018, and precipitation displays a downward trend. The overall NPP_p of alpine grassland demonstrated a downward trend, and precipitation is regarded as the major influencing factor. In addition, the overall NPP_h of alpine grassland exhibited a downward trend. The NPP_a demonstrated an overall upward trend, where 58.32% of the regional NPP_a is in a state of growth, and 41.68% of the regional NPP_a is in a state of degradation. According to contribution analysis, anthropogenic activities provided the primary driving factor to promote the restoration of alpine grassland in Qinghai Province. Moreover, the stocking rate must be reduced in 60.77% of the alpine grasslands in Qinghai Province, mostly situated in the eastern and southwestern parts of Qinghai Province, and the other areas must not increase future stocking rates. The current study can theoretically and technically support the construction of Qinghai as the green organic agricultural and livestock product demonstration province and the creation of an ecological civilization highland.

Keywords: alpine grassland; net primary production; climate change; anthropogenic activities; grazing; stocking rate

Citation: Zhao, L.; Liu, Z.; Hu, Y.; Zhou, W.; Peng, Y.; Ma, T.; Liu, L.; Li, S.; Wang, L.; Mao, X. Evaluation of Reasonable Stocking Rate Based on the Relative Contribution of Climate Change and Grazing Activities to the Productivity of Alpine Grasslands in Qinghai Province. *Remote Sens.* **2022**, *14*, 1455. https://doi.org/10.3390/rs14061455

Academic Editors: Bin Fu, Ruyin Cao and Miaogen Shen

Received: 6 February 2022
Accepted: 15 March 2022
Published: 18 March 2022

1. Introduction

Alpine grassland refers to the main terrestrial ecosystem of the Qinghai–Tibet Plateau, occupying approximately one third of the entire grassland region of China, and has a high sensitivity to environmental changes [1,2]. As one of the crucial resources for human survival and a fundamental environmental element, alpine grassland exerts an essential function in carbon retention, water conservation, animal husbandry production, and biodiversity protection [3–5]. However, recently, the effects of climate change and anthropogenic activities have degraded alpine grasslands, mainly reflected as a decline in grassland net primary productivity (NPP), biodiversity, and water conservation capacity [6–8]. Compared with climate change, anthropogenic activities degrade grassland directly and rapidly and are difficult to quantify. Among such activities, grazing is the most significant disturbing factor in the alpine grassland ecosystem [6,9,10]. Different grazing intensities will cause the grassland ecosystem to exhibit various characteristics. Reasonable grazing, grazing behavior under the condition of forage–livestock balance, will positively influence the grassland ecosystem, stimulate the restoration and improvement of grassland diversity and productivity, and enhance the stability of grassland communities [11,12]. Therefore, evaluating the reasonable stocking rate is crucial, defined as the maximum number of livestock carried on grassland under the condition of maintaining sustainable grassland production, to promote the restoration of alpine grasslands [13].

Present research obtains a reasonable stocking rate by calculating the difference or ratio between the appropriate livestock-carrying ability (the number of standard livestock that can be carried per unit area of grassland per unit of utilization time) of the grassland and the actual carrying ability of grassland [14,15]. Zhang et al. adopted MODIS NPP data to assess the grassland yield in the Three-River Headwaters region, measured the grassland's appropriate livestock-carrying ability, and explored the overgrazing number and the spatial distribution features based on the spatial distribution features on data comparison between actual and appropriate livestock-carrying capacity [14]. Cao et al. adopted climate and remote sensing data to establish a correlation with the aboveground biomass (AGB) of alpine grasslands in the northern Qinghai–Tibet Plateau and analyzed the driving factors of AGB changes in alpine grasslands and evaluated the interannual dynamics of the forage–livestock balance [4]. Thus, it can be seen that the actual productivity of the grassland is often used to convert the proper livestock-carrying ability of the grassland directly. However, grazing is regarded as the most significantly influential anthropogenic activity leading to dynamic changes in the alpine grasslands in Qinghai Province [6,9,10]. The actual productivity of grassland is usually considered to be the difference between the potential productivity of grassland and the productivity of grassland generated by anthropogenic activities [12,16,17]. Assuming that most of the productivity of grassland generated by anthropogenic activities is consumed by grazing, it is unreasonable to use the actual productivity of grassland to replace the grassland productivity generated by anthropogenic activities as the potential consumption of grassland productivity by livestock to estimate the reasonable stocking rate. The methods to quantify the grassland productivity generated by anthropogenic activities are mainly divided into the following two types: the residual trend method and the model-based artificial NPP allocation method [8,18,19]. The residual trend method mainly constructs the function of grassland NPP change with different climatic elements and anthropogenic activities and adopts the equation for estimating each factor's contribution to NPP change for each pixel. For instance, Zhang et al. adopted the residual trend method for exploring the association between NPP and different climatic factors and anthropogenic activities in the Three River Source Region from 1982 to 2012 and quantified the contribution of different driving elements to the interannual variation of NPP [20]. Apart from that, the model-based anthropogenic NPP allocation method mainly simulates the potential NPP of grassland through a climate-driven model and uses a remote sensing model to simulate the actual NPP to define the NPP generated by anthropogenic activities as the difference between the potential NPP and the actual NPP. For instance, Chen et al. applied the terrestrial ecosystem model (TEM) and Carnegie–Ames–Stanford Approach (CASA) to make the simulation of the underlying and actual NPP, respectively, and discussed the influence of climate change and anthropogenic activities on the alpine grasslands on the Qinghai–Tibet Plateau from 1982 to 2011 [19]. In summary, it is necessary for the rational utilization of alpine grassland resources in Qinghai Province to aim to evaluate the reasonable stocking rate based on the grassland productivity generated by anthropogenic activities as the potential consumption of grassland productivity by livestock. Based on our understanding, little research has evaluated the reasonable stocking rate in Qinghai Province by using the relative contribution of climate change and grazing activities to the dynamic alteration of grassland productivity.

Therefore, the objective of this study was to develop a new scenario design method to evaluate the reasonable stocking rate. The specific methods were as follows: following the research of Feng et al. [12], the alpine grassland in Qinghai Province was chosen as the study object in this work, and the Zhou Guangsheng and CASA models were adopted for simulating the potential and actual NPP of the alpine grassland in Qinghai Province from 2005 to 2018. The NPP generated by anthropogenic activities is estimated by the distinction between the potential NPP and the actual NPP. The trend of NPP generated by potential and anthropogenic activities over time is compared to determine the contribution of climate change and anthropogenic activities to the change in NPP in alpine grassland. In addition, the potential and actual grassland productivity consumed by livestock influenced by anthropogenic activities are further discussed, and the influence of grazing on NPP in alpine grassland is analyzed. The driving factors of NPP change and reasonable stocking rate in alpine grassland are then clarified, offering a theoretical foundation for sustainably using alpine grassland resources and the reasonable layout of animal husbandry in Qinghai Province.

2. Materials and Methods

2.1. Study Area

Qinghai Province (89°35′–103°04′E, 31°39′–39°19′N) is located in the northeastern part of the Qinghai–Tibet Plateau, which is also the birthplace of the Yangtze, Yellow, and Lancang Rivers, named as the "Chinese Water Tower". Besides, the total area of Qinghai Province is about 69.67×10^4 km^2 (Figure 1a), and the mean altitude is more than 3000 m [21,22]. According to Koppen climate classification, Qinghai Province mainly includes five climate types: arid desert, cold (BWk), arid steppe, cold (BSK), cold dry winter, warm summer (Dwb), cold dry winter, cold summer (Dwc), and polar tundra (ET) [23]. Alpine grassland is the main ecosystem of Qinghai Province, occupying approximately 59.13% of the total area of the province. It is generally allocated in the Qilian Mountains, Qingnan Plateau, and the edge of the Qaidam Basin. The major grassland types contain alpine meadows and alpine grasslands, as well as temperate grasslands (Figure 1b) [24].

2.2. Data and Processing

The livestock dataset employed in the current work was obtained from Qinghai statistical yearbooks for 2005–2018, and included the annual stock and slaughter numbers of cattle, yaks, cows, horses, mules, donkeys, camels, goats, and sheep (http://tjj.qinghai.gov.cn/tjData/qhtjnj/, accessed on 12 August 2021). We obtained 1801 sample points of alpine grassland AGB data (Figure 1a) from Qinghai Province Natural Resources Comprehensive Investigation and Monitoring Institute. The following sampling methods were employed: based on the stratified sampling method, an alpine grassland investigation quadrat was set in Qinghai Province, and the field investigation was carried out during the peak grass growth period (July–August) from 2005 to 2018. By cutting the grassland in the quadrat, the latitude and longitude, altitude, grassland type, and fresh weight of the aboveground grass production were recorded. The fresh grass was then dried in an oven at 65 °C for 2 days, which was weighed to obtain the aboveground biomass data of the alpine grassland. According to AGB measured data, NPPs in sample points were calculated as:

$$\mathrm{NPP} = \mathrm{AGB}\cdot \mathrm{S_{bn}}\left(1 + \mathrm{S_{ug}}\right), \quad (1)$$

where NPP is net primary productivity, all NPPs' unit is gC·m^{-2}, AGB is the total annual aboveground biomass (AGB) per unit area, g·m^{-2}·a^{-1}, S_{bn} = 0.45 is the conversion factor of grassland biomass into NPP, and S_{ug} is the proportion of belowground to aboveground biomass for diverse grassland kinds. The S_{ug} value refers to the research results of Piao et al. [25]. Among these sample points, 217 NPPs (blue dots in Figure 1a) in the fence (no grazing) were used to verify potential NPP, and the other 1584 NPPs (red dots in Figure 1a) were used to verify actual NPP.

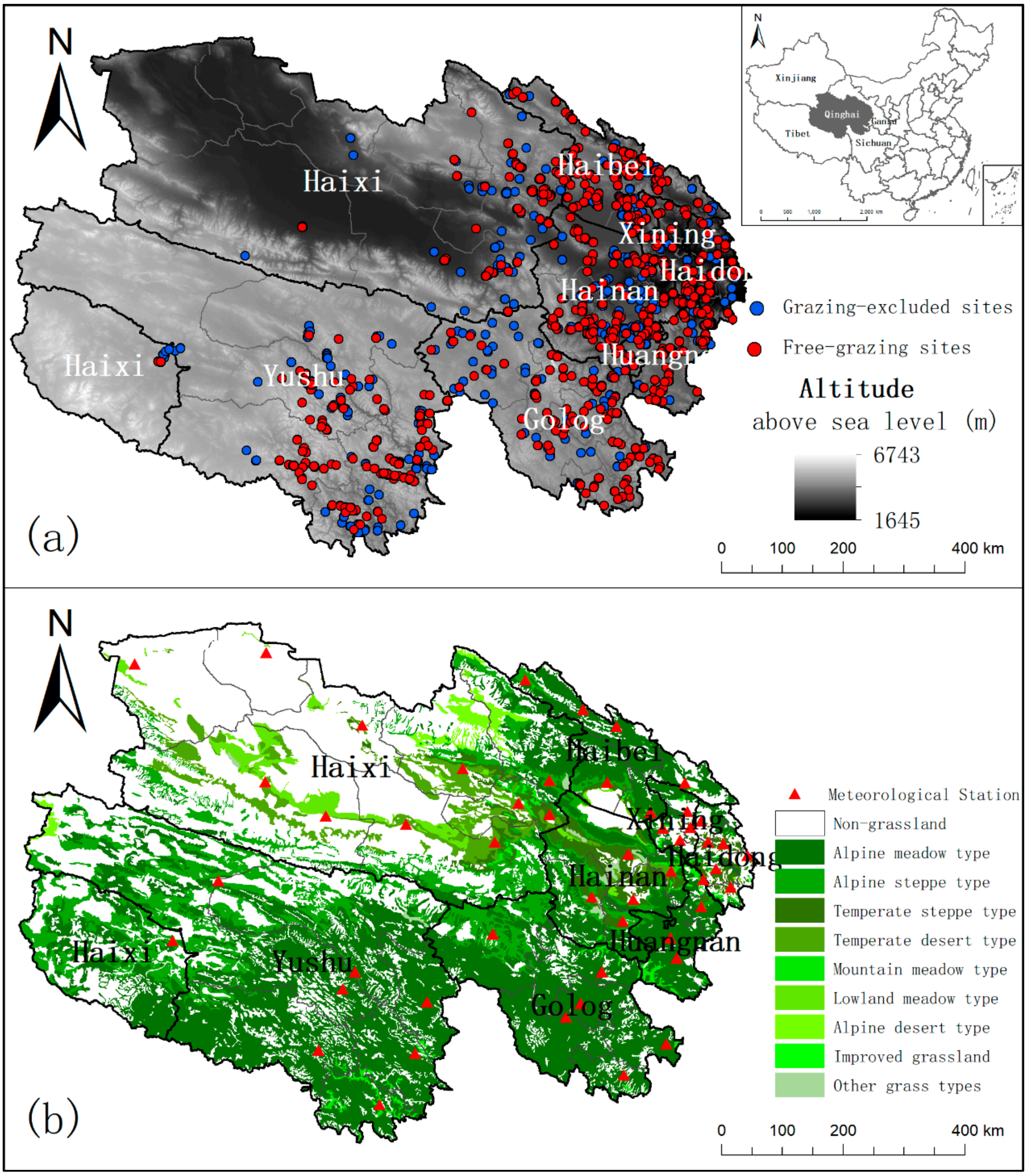

Figure 1. Study area: (**a**) altitude above sea level (http://srtm.csi.cgiar.org/, accessed on 1 November 2019) and verification sites location (grazing-excluded sites in blue, free-grazing sites in red); (**b**) alpine grassland types [24] and meteorological station location.

The remote sensing data mainly included the Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation indices product (MOD13Q1) and MODIS land cover type product (MCD12Q1) (https://ladsweb.modaps.eosdis.nasa.gov/, accessed on 25 August 2021). With the temporal resolution being 16 days, the spatial resolution of MOD13Q1 data reached 250 m. The MOD13Q1 data were preprocessed (such as splicing, projection conversion, and data extraction) by MODIS reconstruction tools (MRT) software (version 4.1). The data were then converted into GeoTIFF format and Albers map projection, and the monthly maximum NDVI data from 2005 to 2018 were obtained based on maximum value composite. With 500-m spatial resolution, the MCD12Q1 data are an annual synthetic product, including five land cover classification schemes. The processing of MCD12Q1 data mainly included using MRT software to convert MCD12Q1 data from HDF to GeoTIFF format through Albers map projection, resampling to 250-m spatial resolution based on the nearest neighbor method (NNM), reclassifying MCD12Q1 data from 2005 to 2018 into six types according to the IGBP global vegetation classification scheme and the reclassification scheme put forward by Ge et al. [26], and then extracting the spatial distribution of grassland for further analysis.

The meteorological datasets, including daily maximum temperature, minimum temperature, average temperature, precipitation, evaporation, relative humidity, wind direction, wind speed, sunshine hours, as well as 0 cm ground temperature, were originated from the National Meteorological Science Data Center (http://data.cma.cn, accessed on 21 June 2020), covering the period 2005–2018. The meteorological data obtained were spatially interpolated by ANUSPLIN software (version 4.2) to obtain the annual monthly average temperature, monthly total precipitation, and monthly total solar radiation from 2005 to 2018. To maintain consistency with the MODIS NDVI data, this study resampled the monthly images to a 250-m spatial resolution. Finally, the WGS-84 datum and Albers equal-area conical projection were used for all monthly images.

2.3. Methods

2.3.1. Estimating NPP_{gap}

As a key indicator of animal husbandry development direction over a defined period, NPP_{gap} is usually used to evaluate the reasonable stocking rate, which is obtained by the time-series average and trend of NPP_{gap} (Table 1). In this study, NPP_{gap} refers to the difference between the NPP generated by anthropogenic activities (NPP_h) and the actual grassland productivity consumed by livestock (NPP_{ac}), and is calculated as follows [12]:

$$NPP_{gap} = NPP_h - NPP_{ac} \tag{2}$$

Table 1. The direction and amplitude of NPP_{gap}.

Mean	Trends	Status of Available Pastures	Current Stocking Rate	Future Stocking Rate
≥0	≥0	Restored	Low	Should be increased
	<0	Restored	Low	Must not be increased
<0	≥0	Degraded	Overgrazed	Should be reduced
	<0	Degraded	Overgrazed	Must be reduced

2.3.2. Estimating NPP_h

The NPP_h is calculated as follows:

$$NPP_h = NPP_p - NPP_a, \tag{3}$$

where NPP_p refers to the potential NPP, and NPP_a denotes the actual NPP. We use the Zhou Guangsheng and CASA models to calculate the NPP_p and NPP_a, respectively. The Zhou Guangsheng model is as follows [27]:

$$NPP_p = RDI^2 \times \frac{P \times \left(1 + RDI + RDI^2\right)}{(1 + RDI)\left(1 + RDI^2\right)} \times Exp\left(-\sqrt{9.87 + 6.25RDI}\right), \tag{4}$$

$$\mathrm{RDI} = \left(0.629 + 0.237\mathrm{PER} - 0.00313\mathrm{PER}^2\right)^2, \tag{5}$$

$$\mathrm{PER} = \frac{\mathrm{BT} \times 58.93}{\mathrm{P}}, \tag{6}$$

$$\mathrm{BT} = \frac{\sum \mathrm{T}}{12}, \tag{7}$$

where RDI stands for the radiation index of dryness, P denotes the total annual precipitation (mm), PER refers to the potential evapotranspiration rate, BT represents the annual average temperature (°C), and T signifies the monthly average temperature (°C).

The CASA model is as follows [28]:

$$\mathrm{NPPa}(x,t) = \mathrm{APAR}(x,t) \times \varepsilon(x,t), \tag{8}$$

$$\mathrm{APAR}(x,t) = \mathrm{SOL}(x,t) \times \mathrm{FPAR}(x,t) \times 0.5, \tag{9}$$

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{max}, \tag{10}$$

where $\mathrm{APAR}(x,t)$ refers to the photosynthetic effective radiation absorbed by pixel x in month t ($MJ \cdot m^{-2}$), $\varepsilon(x,t)$ stands for the actual light energy utilization of pixel x in month t ($gC \cdot MJ^{-1}$), $\mathrm{SOL}(x,t)$ denotes the total solar radiation of pixel x in month t ($MJ \cdot m^{-2}$), the constant 0.5 refers to the ratio of solar effective radiation (400–700 nm) by vegetation in the total solar radiation, and $\mathrm{FPAR}(x,t)$ stands for the absorption proportion of vegetation to incident photosynthetic effective radiation (PAR) with the existence of a good linear relationship with FPAR, NDVI, and SR. Additionally, $T_{\varepsilon 1}(x,t)$ and $T_{\varepsilon 2}(x,t)$ represent the effect of temperature on light energy utilization (°C), $W_{\varepsilon}(x,t)$ represents the impact of water conditions on light energy utilization, and ε_{max} signifies the maximum light energy utilization rate of vegetation in the ideal state. In addition, the value of ε_{max} varies greatly due to different vegetation types ($gC \cdot MJ^{-1}$), and the value mainly refers to the results of previous studies [28–30].

2.3.3. Estimating NPP_{ac}

NPP_{ac} is estimated using the approach of Dong et al. [31], and the formula is as follows:

$$\begin{aligned} \mathrm{NPP_{ac}} = 0.45 \times \mathrm{NSSU_{st}} \times \mathrm{GW} \times \mathrm{GD_{st}} \times (1 - \mathrm{MC}) \times 1000 + 0.45 \times \mathrm{NSSU_{sl}} \times \mathrm{GW} \times \\ \mathrm{GD_{sl}} \times (1 - \mathrm{MC}) \times 1000, \end{aligned} \tag{11}$$

where $NSSU_{st}$ and $NSSU_{sl}$ stand for the number of standard sheep units (heads) of livestock in stock and slaughter, respectively, $GW = 1.8$ refers to the weight of edible hay ($kg \cdot day^{-1}$), $GD_{st} = 365$ and $GD_{sl} = 180$ suggest the number of grass-grazing days for stock and slaughter animals, separately, $MC = 14\%$ suggests the moisture content of dried grass, the constant 0.45 is expressed as the conversion coefficient between biomass and carbon content ($gC \cdot g^{-1}$), and NPP_{ac} is standardized based on the available pasture area at the county level, where the unit is $gC \cdot m^{-2}$.

$$\mathrm{NSSU} = \sum_{i=1}^{n} N_i \times \varepsilon_i, \tag{12}$$

where i denotes the kind of livestock, n stands for the number of livestock types, N_i is the number (heads) of the ith livestock type, and ε_i is the standard sheep conversion coefficient for different livestock. To facilitate the calculation of NPP_{ac}, we employ conversion coefficients to convert diverse livestock into standard sheep units. Besides, the conversion coefficient refers to the Calculation of Proper Carrying Capacity of Rangelands in the Agricultural Industry Standard of China.

In addition, univariate linear regression analysis is adopted for analyzing the temporal and spatial variation trend of alpine grassland NPP in Qinghai Province from 2005 to 2018. The following presents the calculation method:

$$Slope_{NPP} = \frac{n \times \sum_{i=1}^{n} i \times NPP_i - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} NPP_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}, \quad (13)$$

where $Slope_{NPP}$ is the change trend of NPP, $Slope_{NPP} > 0$ indicates the increase of NPP, $Slope_{NPP} < 0$ indicates the decrease of NPP, n = 14 indicates the total time span from 2005 to 2018, where i = 1, 2, 3, . . . , 14 represents the period from 2005 to 2018, with NPP_I representing the annual values of NPP in the year i.

According to the temporal and spatial variation trend of different NPPs, this study assumes four reasons for NPP changes, as shown in Table 2 [16,19,22].

Table 2. Causes of changes in NPP_a.

Hypothesis	Causes of Changes in NPP_a
$sNPP_a \geq 0$ and $sNPP_p \geq sNPP_h$	NPP_a increased because of climate change
$sNPP_a \geq 0$ and $sNPP_p < sNPP_h$	NPP_a increased because of anthropogenic activities
$sNPP_a < 0$ and $sNPP_p \geq sNPP_h$	NPP_a decreased because of climate change
$sNPP_a < 0$ and $sNPP_p < sNPP_h$	NPP_a decreased because of anthropogenic activities

Note: $sNPP_a$, $sNPP_p$, and $sNPP_h$ indicate the slope value of the NPP_a, NPP_p, and NPP_h change trend of each pixel, separately.

The correlation among NPP, temperature, and precipitation is analyzed based on a simple correlation coefficient to understand the response of NPP to different climatic factors. The following presents the calculation formula [12]:

$$R_{xy} = \frac{\sum_{i=1}^{n}\left[(x_i - \overline{x})(y_i - \overline{y})\right]}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}}, \quad (14)$$

where R_{xy} refers to the correlation coefficient, n = 14 represents the total period from 2005 to 2018, x_i denotes the NPP in the ith year, y_i means the temperature or precipitation in the ith year, $\overline{x}$ refers to the mean value of NPP, y_i indicates the mean value of temperature or precipitation, and n stands for the number of samples.

3. Results

3.1. Spatiotemporal Patterns of Precipitation and Temperature in Alpine Grassland in Qinghai Province from 2005 to 2018

This study calculated the temporal and spatial variation trend of precipitation and temperature in alpine grassland in Qinghai Province from 2005 to 2018 using Equation (13) (Figure 2). The mean annual temperature (MAT) of alpine grassland in Qinghai Province was −0.54 °C from 2005 to 2018. Meanwhile, the areas with higher MAT were mainly distributed in areas with relatively low altitudes, such as Xining City, Haidong City, and Hainan Prefecture. The MAT showed a slight upward trend during the 14 years, with an average annual enhancement of 0.04 °C. The increase rate gradually decreased from the central part of Qinghai Province to the east and west sides. The mean annual total precipitation (MAP) of the alpine grassland in Qinghai Province from 2005 to 2018 was 2174.18 mm, and its spatial distribution had obvious spatial heterogeneity. The overall trend increasingly lowered from southeast to northwest. Besides, with the average annual reduction of 125.54 mm, the MAP over 14 years tended to reduce. At the same time, the overall trend of the reduction rate also gradually reduced from southeast to northwest.

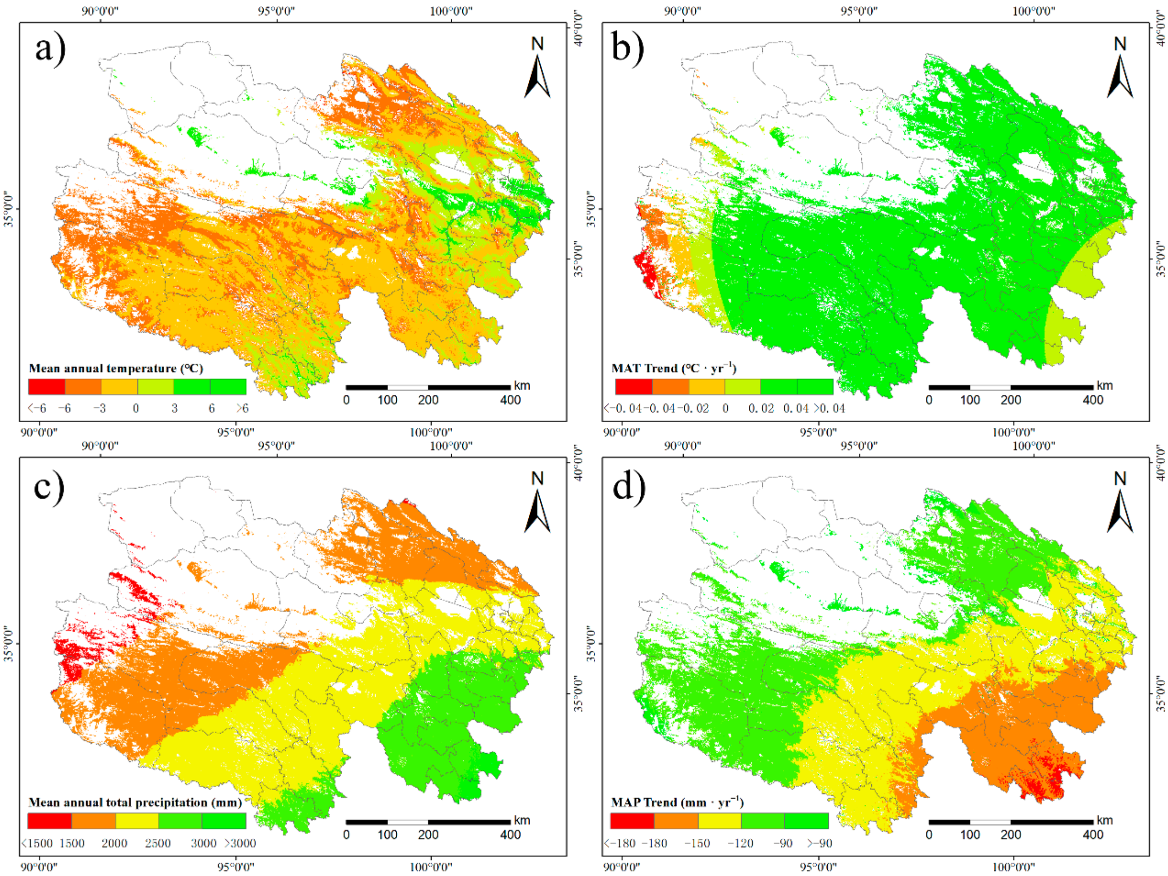

Figure 2. Spatiotemporal patterns of precipitation and temperature in alpine grassland in Qinghai Province from 2005 to 2018. (**a**) Mean annual temperature (MAT), (**b**) change trend of MAT, (**c**) mean annual total precipitation (MAP), and (**d**) change trend of MAP.

3.2. Spatiotemporal Patterns of Alpine Grassland NPP_p, NPP_a, and NPP_{ac} in Qinghai Province from 2005 to 2018

In this study, the mean annual NPP_p and NPP_a in Qinghai Province from 2005 to 2018 were estimated using Zhou Guangsheng and CASA models, respectively. The results can be found in Figure 3a,c. The spatiotemporal patterns of alpine grassland NPP_{ac} calculated using Equation (11) are shown in Figure 3e. The mean annual NPP_p of alpine grassland in Qinghai Province from 2005 to 2018 was 419.11 $gC{\cdot}m^{-2}$. In addition, its spatial distribution also gradually reduced from southeast to northwest, showing consistency with the MAP. The change in NPP_p in the past 14 years presented a downward trend, with the average annual decrease of 25.45 $gC{\cdot}m^{-2}$. Moreover, the overall trend of the reduction rate also conformed to the MAP, indicating that NPP_p was closely related to precipitation. The mean annual NPP_a was 423.42 $gC{\cdot}m^{-2}$. The areas with higher values were generally distributed in the eastern part of Qinghai Province and the overall trend also progressively decreased from southeast to northwest. During the 14 years, 58.32% of the alpine grassland NPP in Qinghai Province was in a state of growth and 41.68% of the area experienced degradation. The degraded area was mainly located in Yushu and Golog Prefectures and the middle of Haibei Prefecture. Compared with the overall decrease in NPP_p, the ecological construction projects carried out by Qinghai Province in recent years achieved better results. Besides, the mean annual NPP_{ac} was 34.51 $gC{\cdot}m^{-2}$. In addition, the areas with high value mainly were arranged in the east of Qinghai Province, such as Xining City, Haidong City, Huangnan Prefecture, Haibei Prefecture, etc., indicating that the actual livestock-carrying capacity in these areas was greater than the theoretical livestock-carrying capacity. There were fewer available pastures in these areas compared with other areas. During the 14 years, 84.25% of alpine grassland NPP_{ac} in Qinghai Province tended to increase, but the trend was relatively low, with the average annual growth of 0.43 gC·m^{-2}, and only 15.75% of the area was in a downward trend. This area was mainly located in Maduo, Maqin, Gande, Dari, Bama, and Zeku Counties.

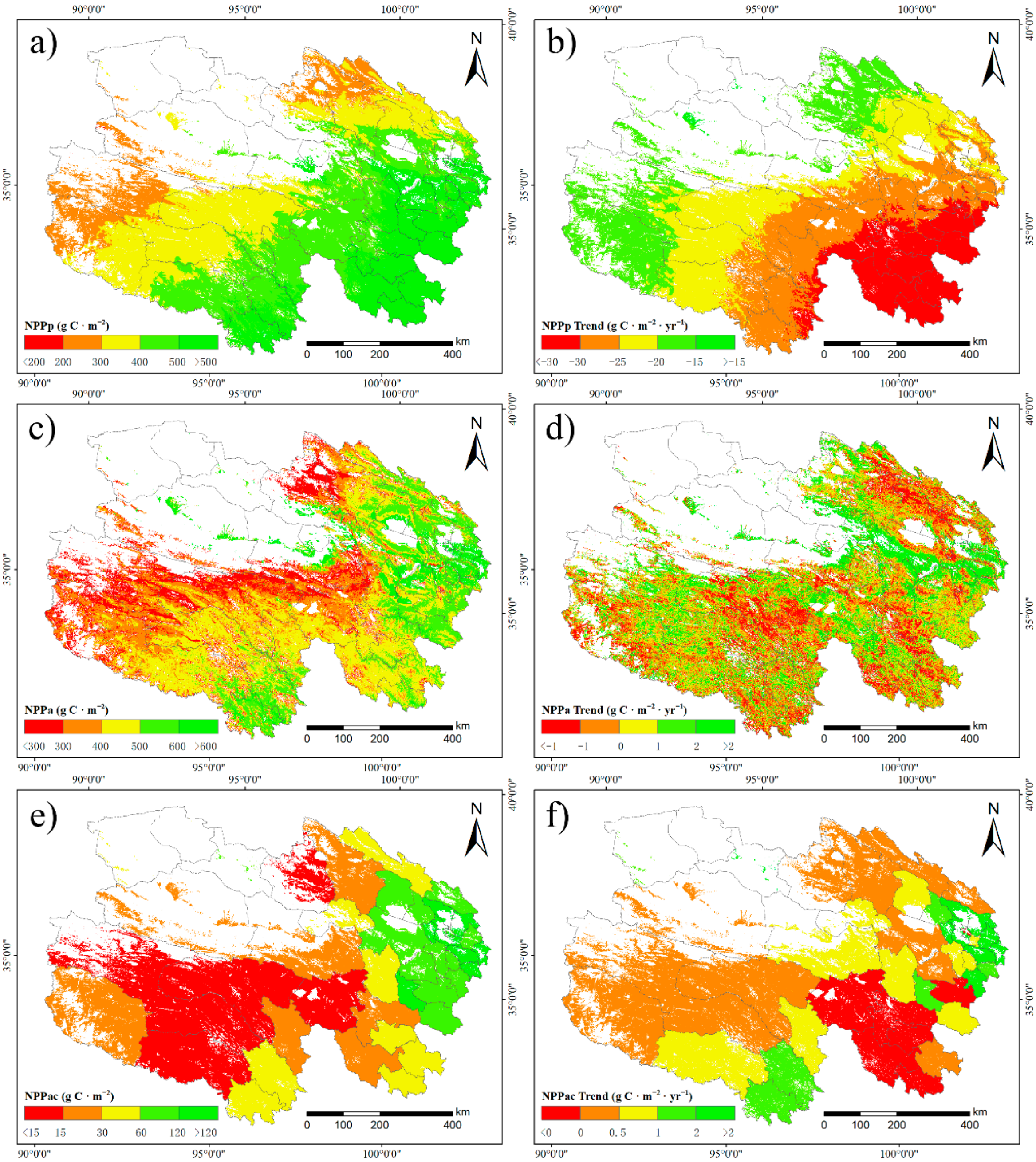

Figure 3. Spatiotemporal patterns of NPP_p, NPP_a, and NPP_{ac} in alpine grassland in Qinghai Province from 2005 to 2018: (**a**) mean annual NPP_p; (**b**) change trend of NPP_p; (**c**) mean annual NPP_a; (**d**) change trend of NPP_a; (**e**) mean annual NPP_{ac}; (**f**) change trend of NPP_{ac}.

The simulated results (NPP_p and NPP_a) were verified based on the measured data (Figure 4). Based on the obtained results, there existed an obvious positive association between the measured NPP data and the simulated NPP data. The R^2 between the measured NPP and the NPP_p was 0.60 (p < 0.001), the RMSE reached 101.73 gC·m^{-2}·yr^{-1}, with the MAE being 82.86. Additionally, the R^2 between the measured NPP and the NPP_a reached 0.71 (p < 0.001) and the RMSE was 61.38 gC·m^{-2}·yr^{-1}, with the MAE being 50.66.

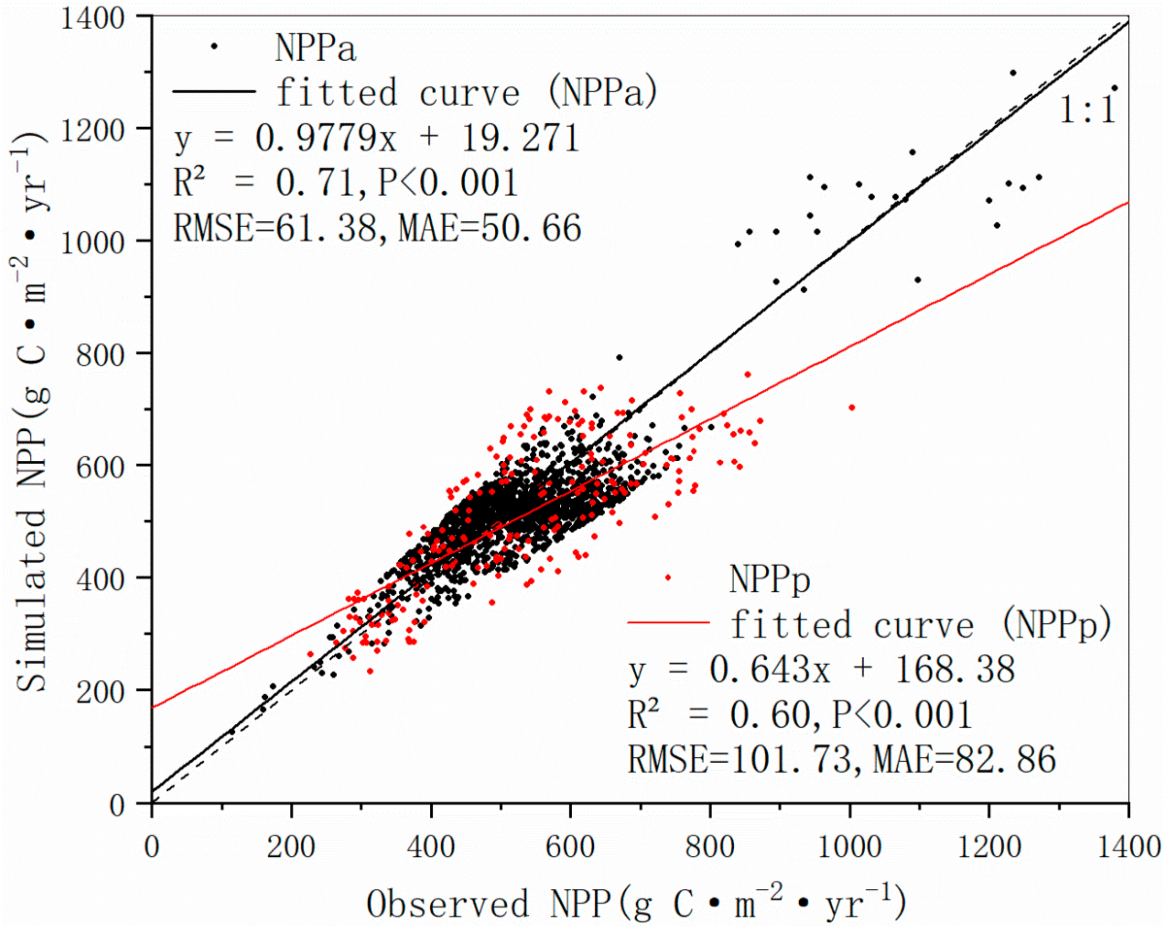

Figure 4. Ground validation of NPP_p and NPP_a.

3.3. Spatiotemporal Patterns of Alpine Grassland NPP_h and NPP_{gap} in Qinghai Province from 2005 to 2018

The spatiotemporal patterns of alpine grassland NPP_h and NPP_{gap} in Qinghai Province from 2005 to 2018 calculated using Equations (2) and (3) are shown in Figure 5. The change in NPP_h was related to NPP_p and NPP_a. According to the calculation formula of NPP_h, the mean annual NPP_h in alpine grassland of Qinghai Province from 2005 to 2018 was -12.34 gC·m^{-2}. The areas with low mean annual value mainly were allocated in the northeast and southwest of Qinghai Province, such as Haibei Prefecture, Xining City, and Yushu Prefecture. The change in NPP_h in the past 14 years showed an overall downward trend, with an average annual decrease of 26.26 gC·m^{-2}. The overall trend of the decrease rate also gradually decreased from southeast to northwest. The change in NPP_{gap} was related to NPP_h and NPP_{ac}. The mean annual value was -46.89 gC·m^{-2}. The regions with lower values were basically the same as those with lower values of NPP_h. In the past 14 years, the rate of change of NPP_{gap} also predominately presented a downward trend, with the average annual reduction of 26.91 gC·m^{-2}. In addition, the overall trend of the decrease rate was also consistent with the trend of NPP_h.

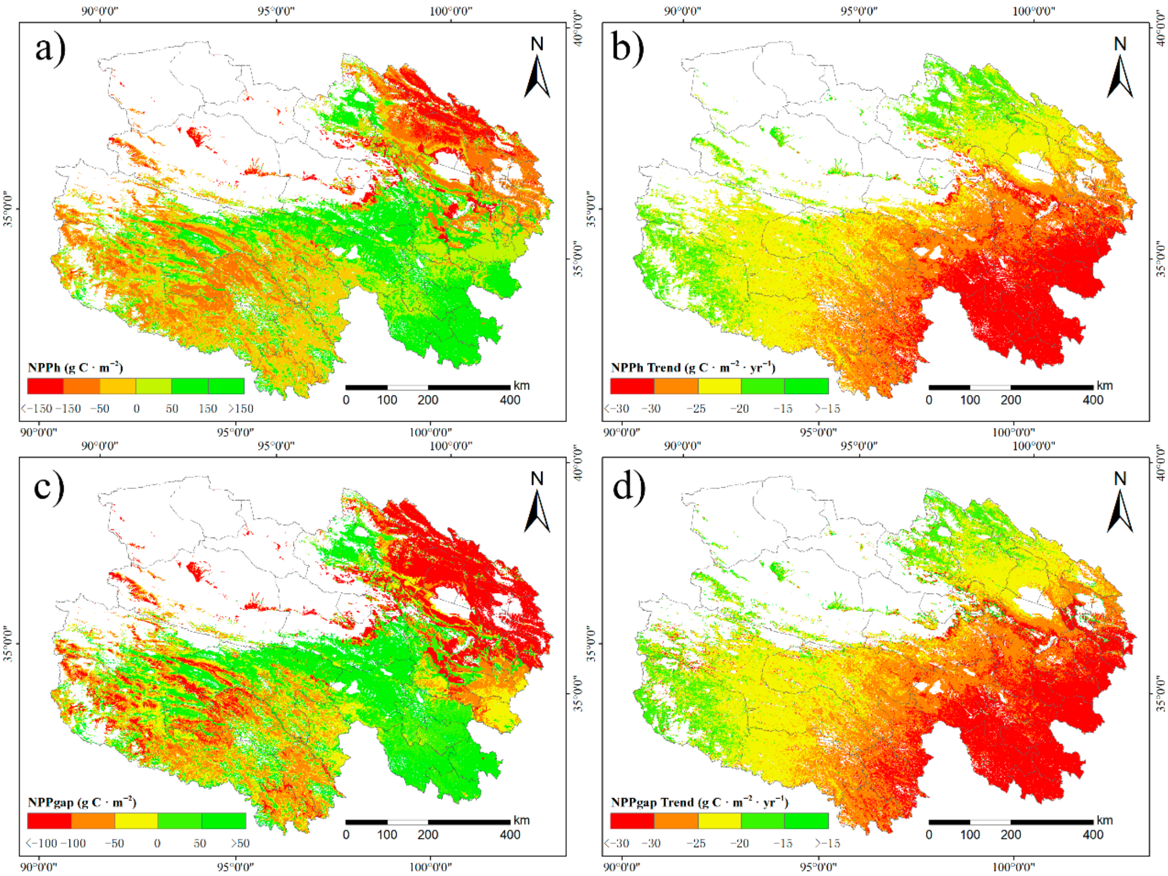

Figure 5. Spatiotemporal patterns of NPP_h and NPP_{gap} in alpine grassland in Qinghai Province from 2005 to 2018: (**a**) mean annual NPP_h; (**b**) change trend of NPP_h; (**c**) mean annual NPP_{gap}; (**d**) change trend of NPP_{gap}.

3.4. Correlation Analysis of NPP with Climate in Alpine Grassland in Qinghai Province from 2005 to 2018

The characteristics of the above five different NPPs reflect the spatial heterogeneity of climate and topography and the gradient of temperature and precipitation in Qinghai Province. They also reflect the intensity of anthropogenic activities. To better understand the response of NPPs to different climatic factors, we carried out a correlation analysis of five different NPPs with temperature and precipitation. The results are shown in Figures 6 and 7. From 2005 to 2018, the correlation coefficient between NPP_p and temperature of alpine grassland in Qinghai Province was between −0.73 and 0.66, and there was no high correlation. Among them, 95.09% of alpine grassland NPP_p showed a negative association with temperature. NPP_p and precipitation were positively associated and highly correlated, with correlation coefficients greater than 0.8, indicating that precipitation was regarded as the major element influencing the NPP_p. The average correlation coefficient between NPP_a and the temperature was 0.21, 81.49% of the areas had correlation coefficients between −0.4 and 0.4, and the correlation was not significant. NPP_a was mainly positively correlated with temperature, and only 15.54% of the areas were negatively correlated with temperature, mostly situated in the central part of Yushu and Haibei Prefecture, southern Haixi Prefecture, and southern Haidong City. The correlation between NPP_a and precipitation was also not significant, 85.32% of the areas had correlation coefficients between −0.4 and 0.4, and 37.30% of the areas showed a positive association with precipitation, mainly located in the central part of Yushu Prefecture, Haibei Prefecture, and Golmud City. The temporal and spatial difference of the correlation coefficient was not obvious. The correlation coefficient between NPP_{ac} and the temperature was between −0.38 and 0.64, and there was no high correlation. Additionally, 80.03% of the areas showed a positive correlation with temperature, and the areas negatively correlated with temperature were mainly located in Tianjun, Maduo, Maqin, Dari, and Banma Counties. The average correlation coefficient between NPP_{ac} and precipitation was −0.38, 74.96% of the areas were negatively related to precipitation, and the positively associated areas were mainly located in Golog Prefecture, Golmud City, and Zeku County.

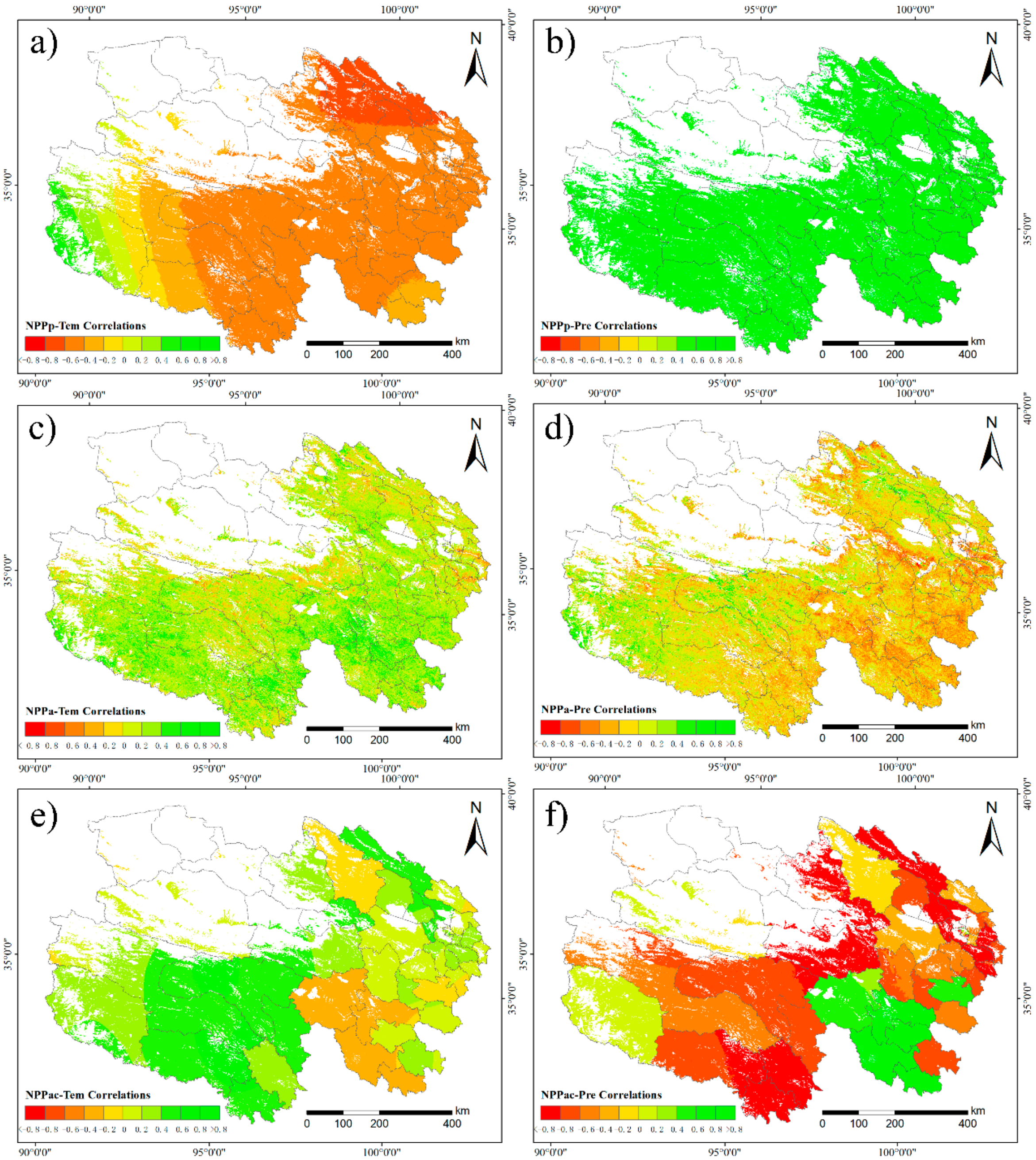

Figure 6. Correlations of NPP_p, NPP_a, and NPP_{ac} with climate in alpine grassland in Qinghai Province from 2005 to 2018: (**a**) correlation coefficient between NPP_p and temperature; (**b**) correlation coefficient between NPP_p and precipitation; (**c**) correlation coefficient between NPP_a and temperature; (**d**) correlation coefficient between NPP_a and precipitation; (**e**) correlation coefficient between NPP_{ac} and temperature; (**f**) correlation coefficient between NPP_{ac} and precipitation.

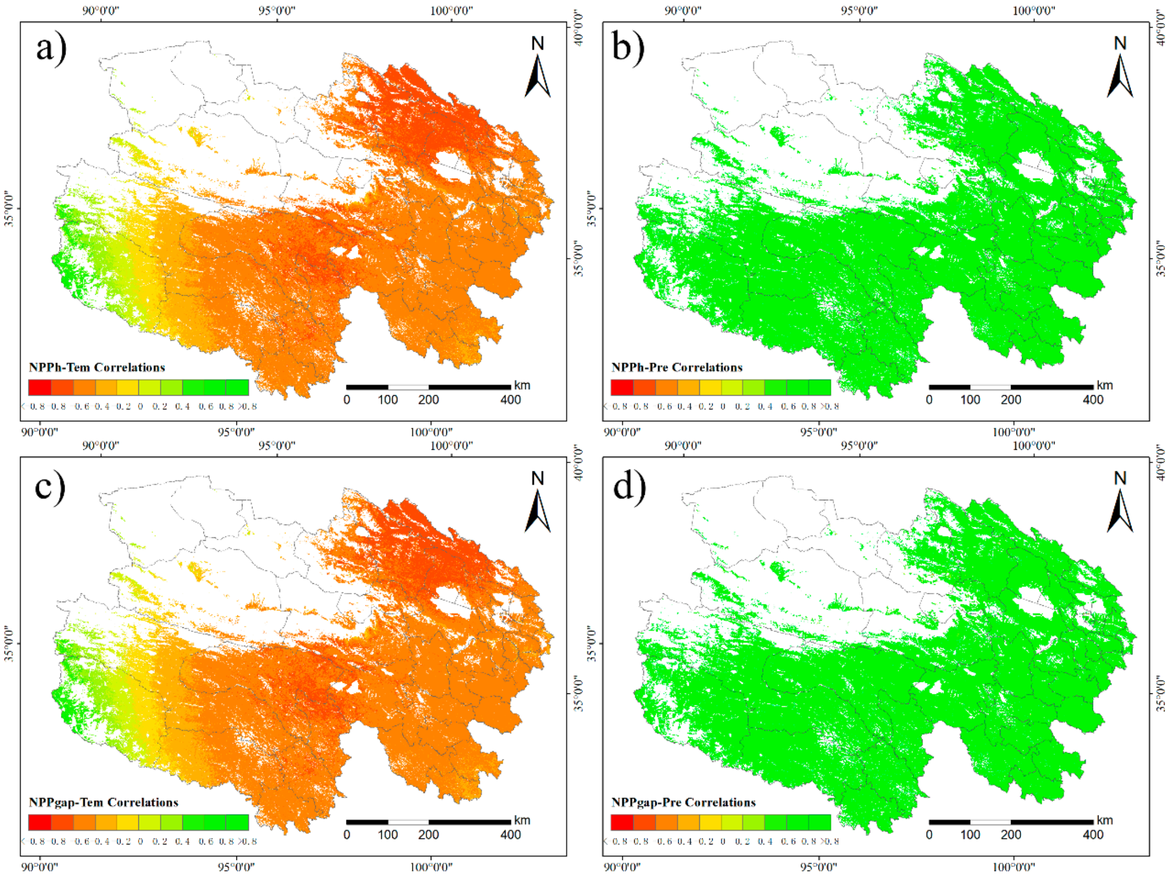

Figure 7. Correlations of NPP_h and NPP_{gap} with climate in alpine grassland in Qinghai Province from 2005 to 2018: (**a**) correlation coefficient between NPP_h and temperature; (**b**) correlation coefficient between NPP_h and precipitation; (**c**) correlation coefficient between NPP_{gap} and temperature; (**d**) correlation coefficient between NPP_{gap} and precipitation.

In addition, the average correlation coefficient between NPP_h and the temperature was −0.44. On the whole, 92.84% of the regions exhibited a negative connection to temperature, and NPP_h showed a positive correlation with precipitation and was strongly associated, with the correlation coefficients greater than 0.8. Apart from that, the correlation between NPP_{gap} and climate was consistent with the correlation between NPP_h and climate, which was negatively related to temperature and had a highly positive correlation with precipitation.

3.5. Evaluation of Reasonable Stocking Rate Based on the Relative Contribution of Climate Change and Grazing Activities to the Productivity of Alpine Grasslands in Qinghai Province

In this study, the contributions of climate change and anthropogenic activities to the increase and decrease in grassland NPP were controlled by superimposing the change trends of NPP_p, NPP_a, and NPP_h. Based on the above NPP_a results, the reasons for NPP_a changes were analyzed according to Table 2. Figure 8 presents the results. A total of 41.68% of the alpine grassland in Qinghai Province was in a decreased state, mainly located in Yushu and Golog Prefectures and the central area of Haibei Prefecture. This was due to the enhancement in temperature and the reduction in precipitation in Qinghai Province over the 14 years, which increased the evaporation of alpine grassland during growth and development and aggravated land desertification and salinization, leading to potential productivity reductions. In the meanwhile, due to a series of policies carried out by the Qinghai Provincial Government, such as the Returning Grazing to Grassland Project (RGGP), which was launched in 2003, to strengthen grassland ecological protection and construction, restore grassland productivity, improve grassland ecological environment and herdsmen's living standards, and to promote the sustainable development of grassland animal husbandry [32]. Grassland Ecological Protection Subsidy and Award Policy (GEPSAP) started in 2011, mainly through the implementation of grazing prohibition subsidies, forage–livestock balance incentives, and other ways to give subsidies to herders to limit the large-scale degradation of grasslands [33,34]. The Three River Source Ecological Protection and Construction Project (TRSEPCP), including Yushu Prefecture, Golog Prefecture, Hainan Prefecture, Huangnan Prefecture, and Golmud City, began in 2005, accounting for 54.6% of the total area of Qinghai Province. In terms of grassland ecological protection, the project mainly focuses on grassland vegetation protection and restoration, implements GEPSAP and RGGP, and conducts special treatment of "Black Beach" type degraded grassland to increase grassland vegetation coverage and biomass yield (https://www.ndrc.gov.cn/fzggw/jgsj/njs/sjdt/201404/t20140411_1194723.html?code=&state=123, accessed on 20 January 2022) [35]. Anthropogenic activities gradually emerged as the driving element affecting the growth of alpine grassland and promoted the restoration of alpine grassland in Qinghai Province. Besides, the increase in the NPP_a area accounted for 58.32% of the entire area of the alpine grassland, mostly located in Huangnan, Hainan, and Haixi Prefectures and the western area of Yushu Prefecture.

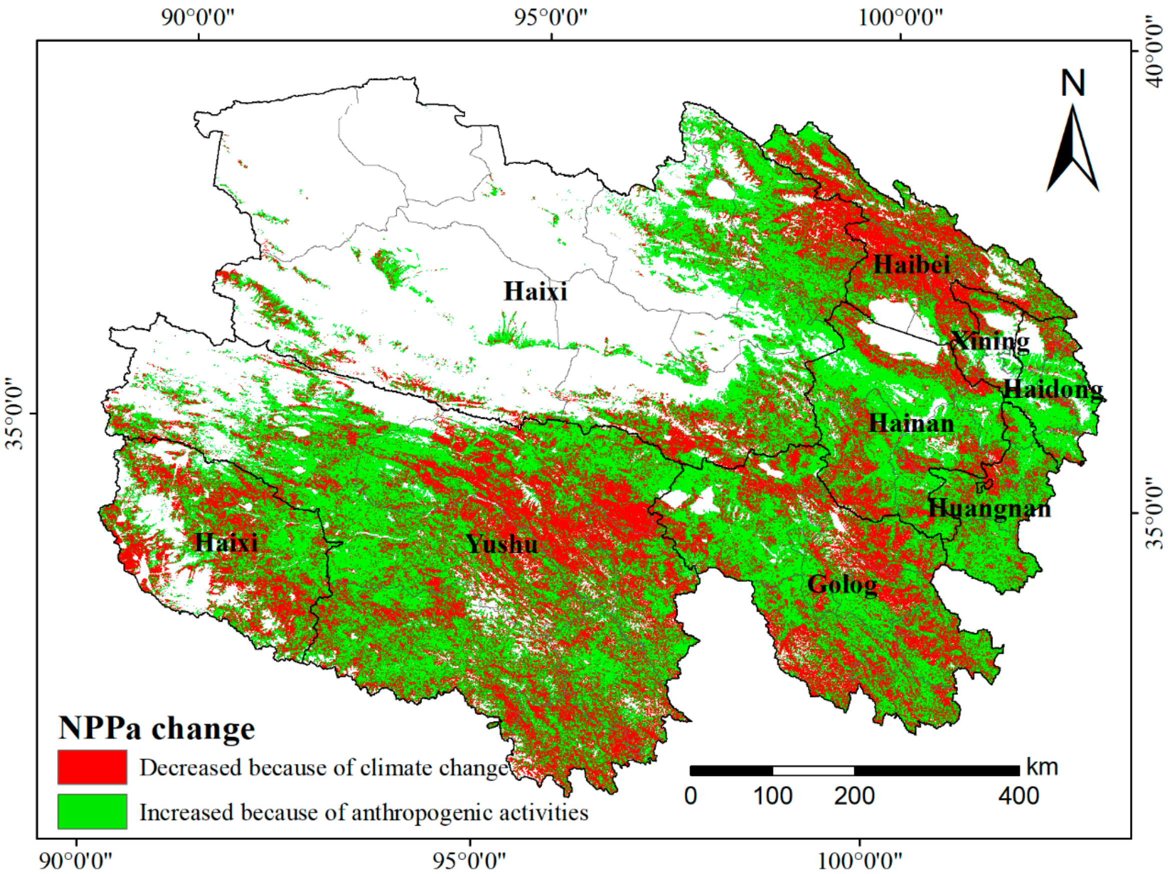

Figure 8. Spatial patterns of driving factors for NPP_a changes in alpine grassland in Qinghai Province from 2005 to 2018.

Figure 9 shows the spatial patterns of future stocking rates according to Table 1. From 2005 to 2018, 60.77% of the alpine grasslands in Qinghai Province were overloaded with livestock consumption productivity, and the stocking rate of livestock was high. The available pastures were already in a degraded state and mostly positioned in the eastern and southwestern parts of Qinghai Province, such as Haibei Prefecture, Xining City, Huangnan Prefecture, Haidong City, and parts of Yushu Prefecture and Golmud City. This result is attributed to the relatively high population density in the eastern parts of Qinghai Province, combined with a lower number of available pastures. To meet the daily consumption of human beings, the grassland was overused, leading to grassland degradation. In addition, because of the relatively high altitude, the temperature and precipitation are comparatively low in the southwest of Qinghai Province. The ecosystem in this region was extremely fragile, coupled with long-run overgrazing, resulting in the flood of grassland rodents and pests in the southwest of Qinghai Province, grassland production decreasing sharply, the contradiction between "human-forage-livestock" increasing, and grassland animal husbandry being severely tested [36]. Here, 39.23% of the areas were at a critical state of livestock consumption productivity and the stocking rate of livestock was relatively low. Overgrazing in this overloaded area must be reduced in the future to recover available pastures to some extent. To further restore the productivity of alpine grasslands, livestock-carrying capacity should not be increased.

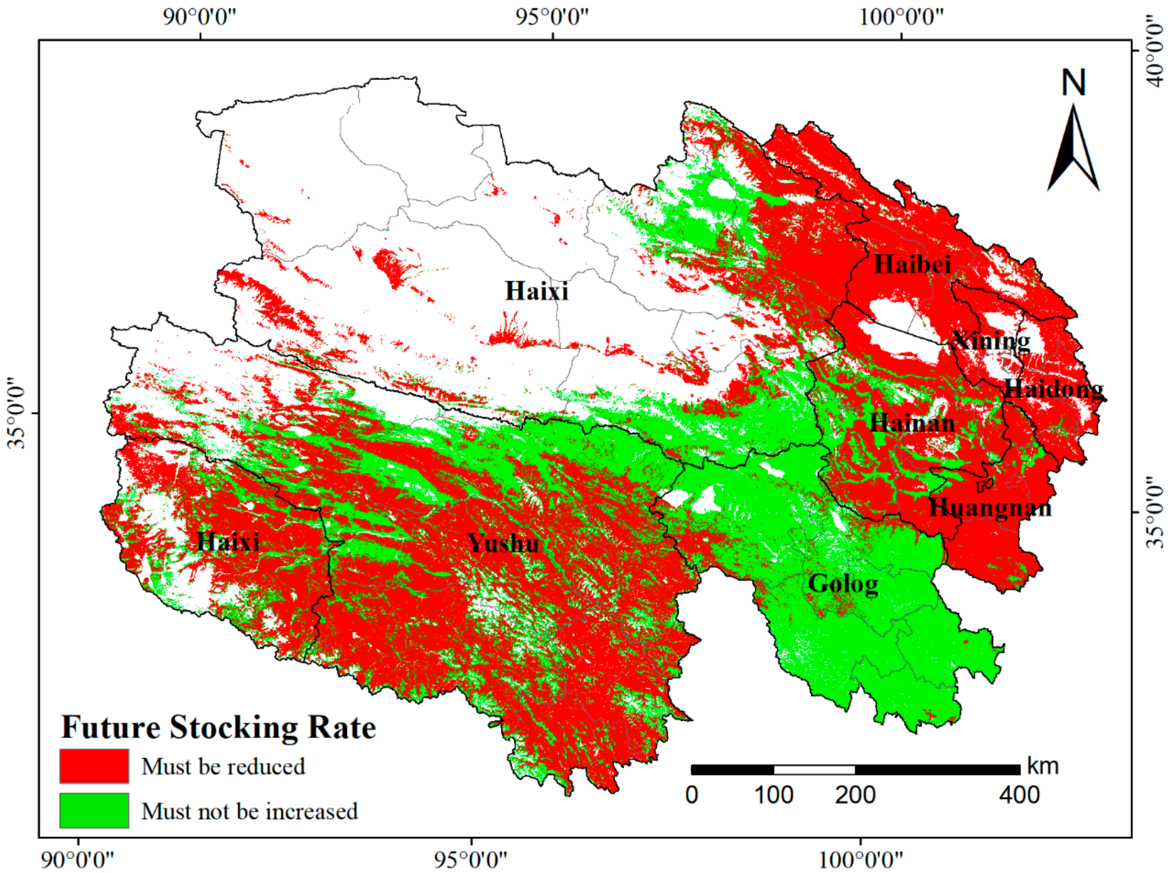

Figure 9. Spatial patterns of future stocking rates.

4. Discussion

4.1. Methods

This study regards climate change and anthropogenic activities as the leading driving elements for the dynamic changes in grassland productivity. Traditional methods mainly rely on field surveys or social statistics to evaluate the effect of climate change and anthropogenic activities on grassland degradation. However, this method is time-consuming and labor-intensive, especially in areas that lack statistical data or where human surveys are difficult to conduct [16,37]. In this study, remote sensing and meteorological data were used as input parameters, and NPP was chosen as the indicator to monitor the dynamic changes in alpine grassland. The Zhou Guangsheng and CASA models were adopted to simulate the potential and actual NPP of alpine grassland. Until now, a large number of researches have determined the contribution of climate change and anthropogenic activities to the change of grassland NPP by contrasting the trends of potential and actual NPP of grassland over time to realize the quantitative evaluation of the driving factors of grassland change [16,18,19]. However, the above studies were conducted assuming that grassland growth was only controlled by climate change and anthropogenic activities, ignoring the effect of grazing activities. Therefore, in the grassland productivity simulation model based on remote sensing, the grassland productivity actually consumed by livestock should be considered to reflect the actual grassland productivity that is genuinely affected by climate change and anthropogenic activities. Referring to the method proposed by Feng et al. [12], it was found that 58.32% of alpine grassland NPP_a in Qinghai Province was in an increased state, mainly located in Huangnan, Hainan, and Haixi Prefectures and the western area of Yushu prefecture. Additionally, 41.68% of the area was in a decreased state, mainly located in Yushu and Golog Prefectures and the central area of Haibei Prefecture. Anthropogenic activities were the main driving element for restoring alpine grassland in Qinghai Province. The results were similar to previous research results [16,37]. In addition, by analyzing the influence of grazing on the NPP of alpine grassland in Qinghai Province, it could be concluded that 60.77% of alpine grassland areas in Qinghai Province from 2005 to 2018 must reduce livestock-carrying capacity in the future, particularly in the eastern and south-western parts of Qinghai Province. Apart from that, 39.23% of the areas should not increase livestock-carrying capacity in the future, which is consistent with former research [36,38].

4.2. Impacts of Different Driving Factors on Alpine Grassland NPP

Climate is regarded as the vital biophysical element influencing the growth of vegetation, while temperature and precipitation are essential elements affecting the interannual variability of vegetation [39]. From 2005 to 2018, the temperature of the alpine grassland in Qinghai Province tended to increase slightly, and the precipitation tended to reduce, which conformed to the previous research results [19]. Climate change has made the ecological environment of alpine grasslands more vulnerable and increasingly sensitive to grassland degradation caused by anthropogenic activities. By comparing the change trend between climate factors and different alpine grassland NPP in Qinghai Province, it could be found that the change trend of NPP_p was in good agreement with precipitation, suggesting that the grassland growth was more sensitive to precipitation. Previous studies have also reached similar conclusions [16]. In addition, the NPP_p of alpine grasslands in Qinghai Province was mainly negatively related to temperature and highly positively connected to precipitation, which further indicated that precipitation was the major element influencing the alpine grasslands NPP_p. Nevertheless, the change trend of NPP_a was consistent with precipitation and temperature, which may be caused by the intervention of anthropogenic activities in various years. The correlation results showed that NPP_a showed a positive correlation with temperature. Meanwhile, the spatial and temporal difference in the correlation with precipitation was not obvious, indicating that temperature was the major element for the enhancement of NPP_a, which was consistent with the results of previous studies [37,40]. Numerous studies have demonstrated that anthropogenic activities are the main driving factor leading to the grassland dynamic changes [12,16,41]. From 2005 to 2018, the NPP_a increased area of alpine grassland in Qinghai Province was more than that of decreased areas, which may be associated with the ecological construction projects conducted in Qinghai Province recently. However, in the past 14 years, NPP_h has shown a decreasing trend, and its change trend was consistent with NPP_p, indicating that the major cause of the decrease in NPP_h was likely to be climate change, but the impact of the anthropogenic activity of grazing on its changes was not excluded. By calculating the change trend of NPP_{ac}, it was concluded that NPP_{ac} mainly increased in the past 14 years, which further proved that the increase in livestock capacity was also the predominant reason for the decrease in NPP_h.

This study firstly determined the relative contribution of climate change and grazing activities to the productivity of alpine grassland to evaluate the reasonable stocking rate in Qinghai Province. The research results showed that, although NPP_{ac} has mainly tended to increase in the previous 14 years, with the year-on-year increase in NPP_a, 60.77% of the alpine grassland areas in Qinghai Province must reduce their carrying capacity for the time to come, mostly in the eastern and southwestern parts of Qinghai Province, and the remaining areas should not increase the carrying capacity in the future. In summary, the series of policies conducted by the Qinghai Provincial Government, such as the Returning Grazing to Grassland Project, Grassland Ecological Protection Subsidy and Award Policy, and the Three River Source Ecological Protection and Construction Projects, have yielded fruitful results in the prevention of grassland degradation and keeping the balance between grass and livestock. All policies and projects have generated positive ecological impacts. At the same time, anthropogenic activities have become the leading element in restoring alpine grassland in Qinghai Province.

4.3. Limitations and Uncertainties

We evaluated the reasonable stocking rate under the condition that human activities only included grazing. However, the impact of anthropogenic activities on NPP changes in alpine grasslands also includes population migration and land-use changes. We will consider the impact of such other anthropogenic activities and add ecological footprint and biocapacity to evaluate the reasonable stocking rate in future work [42,43]. Moreover, because of the low spatial resolution of MODIS images and the presence of mixed pixels, the NPP simulation accuracy of alpine grassland was relatively low due to the influence of other ground features. In subsequent research, the mixed pixel decomposition method will be used to obtain grassland information and improve the simulation accuracy of NPP.

5. Conclusions

To conclude, the current work considered the influence of the relative contribution of climate change and grazing activities on the productivity of alpine grassland to evaluate the reasonable stocking rate in Qinghai Province. Overall, from 2005 to 2018, 58.32% of alpine grassland NPP_a in Qinghai Province was in an increased state, mainly located in Huangnan, Hainan, and Haixi Prefectures and the western area of Yushu Prefecture. Additionally, 41.68% of the area was in a degraded state, mainly located in Yushu and Golog Prefectures and the central area of Haibei Prefecture. Contribution analysis showed that anthropogenic activities were the main driving factor in promoting the restoration of alpine grassland. According to the data assessment of the reasonable stocking rate from 2005 to 2018, 60.77% of the alpine grasslands in Qinghai Province must reduce their carrying capacity in the time to come, particularly in the eastern and southwestern parts of Qinghai Province, while the other areas should not increase the carrying capacity in the future. The results were scientifically significant and can be used to promote the maintainable use of alpine grassland resources and the rational distribution of animal husbandry in Qinghai Province.

Author Contributions: Conceptualization, L.Z. and Z.L.; methodology, L.Z. and Z.L.; software, W.Z. and T.M.; validation, W.Z., Y.P. and T.M.; investigation, L.W. and Y.H.; resources, L.W. and Y.H.; data curation, L.Z., W.Z. and Y.P.; writing—original draft preparation, L.Z.; writing—review and editing, Z.L., S.L., L.L. and X.M.; funding acquisition, Y.H. and L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The National Key Research and Development Program of China (No. 2020YFD1100203) and Qinghai Province Science and Technology Planning Project (No. 2019-HZ-801).

Data Availability Statement: Not applicable.

Acknowledgments: We are appreciative for the paper writing assistance of Wenwen Ma and Afei Lu.

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

References

1. Zhao, P.; Qu, J.; Xu, X.; Tang, J.; Han, Q.; Xie, S.; Wang, T.; Lai, J. Study on the characteristics of sandy alpine grasslands and its relationship between plant distribution and microtopography in the source regions of Yangtze River. *Acta Ecol. Sin.* **2019**, *39*, 1030–1040. (In Chinese)
2. Fayiah, M.; Dong, S.; Li, Y.; Xu, Y.; Gao, X.; Li, S.; Shen, H.; Xiao, J.; Yang, Y.; Wessell, K. The relationships between plant diversity, plant cover, plant biomass and soil fertility vary with grassland type on Qinghai-Tibetan Plateau. *Agric. Ecosyst. Environ.* **2019**, *286*, 106659. [CrossRef]
3. Li, H.; Wang, C.; Zhang, F.; He, Y.; Shi, P.; Guo, X.; Wang, J.; Zhang, L.; Li, Y.; Cao, G.; et al. Atmospheric water vapor and soil moisture jointly determine the spatiotemporal variations of CO_2 fluxes and evapotranspiration across the Qinghai-Tibetan Plateau grasslands. *Sci. Total Environ.* **2021**, *791*, 148379. [CrossRef] [PubMed]
4. Cao, Y.; Wu, J.; Zhang, X.; Niu, B.; Li, M.; Zhang, Y.; Wang, X.; Wang, Z. Dynamic forage-livestock balance analysis in alpine grasslands on the Northern Tibetan Plateau. *J. Environ. Manag.* **2019**, *238*, 352–359. [CrossRef] [PubMed]
5. Ran, Q.; Hao, Y.; Xia, A.; Liu, W.; Hu, R.; Cui, X.; Xue, K.; Song, X.; Xu, C.; Ding, B.; et al. Quantitative Assessment of the Impact of Physical and Anthropogenic Factors on Vegetation Spatial-Temporal Variation in Northern Tibet. *Remote Sens.* **2019**, *11*, 1183. [CrossRef]
6. Bardgett, R.D.; Bullock, J.M.; Lavorel, S.; Manning, P.; Schaffner, U.; Ostle, N.; Chomel, M.; Durigan, G.; Fry, E.L.; Johnson, D.; et al. Combatting global grassland degradation. *Nat. Rev. Earth Environ.* **2021**, *2*, 720–735. [CrossRef]
7. Bai, Y.; Guo, C.; Degen, A.A.; Ahmad, A.A.; Wang, W.; Zhang, T.; Li, W.; Ma, L.; Huang, M.; Zeng, H.; et al. Climate warming benefits alpine vegetation growth in Three-River Headwater Region, China. *Sci. Total Environ.* **2020**, *742*, 140574. [CrossRef]
8. Deng, X.; Gibson, J.; Wang, P. Quantitative measurements of the interaction between net primary productivity and livestock production in Qinghai Province based on data fusion technique. *J. Clean. Prod.* **2017**, *142*, 758–766. [CrossRef]
9. Yu, H.; Ding, Q.; Meng, B.; Lv, Y.; Liu, C.; Zhang, X.; Sun, Y.; Li, M.; Yi, S. The Relative Contributions of Climate and Grazing on the Dynamics of Grassland NPP and PUE on the Qinghai-Tibet Plateau. *Remote Sens.* **2021**, *13*, 3424. [CrossRef]
10. Harris, R.B. Rangeland degradation on the Qinghai-Tibetan plateau: A review of the evidence of its magnitude and causes. *J. Arid Environ.* **2010**, *74*, 1–12. [CrossRef]
11. Du, Y.; Ke, X.; Guo, X.; Cao, G.; Zhou, H. Soil and plant community characteristics under long-term continuous grazing of different intensities in an alpine meadow on the Tibetan plateau. *Biochem. Syst. Ecol.* **2019**, *85*, 72–75. [CrossRef]
12. Feng, Y.; Wu, J.; Zhang, J.; Zhang, X.; Song, C. 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. *Remote Sens.* **2017**, *9*, 136. [CrossRef]
13. Hou, X.; Yin, Y.; Michalk, D.; Yun, X.; Ding, Y.; Li, X.; Ren, J. Herders' opinions about desirable stocking rates and overstocking in the rangelands of northern China. *Rangel. J.* **2014**, *36*, 601. [CrossRef]
14. Zhang, J.; Zhang, L.; Liu, W.; Qi, Y.; Wo, X. Livestock-carrying capacity and overgrazing status of alpine grassland in the Three-River Headwaters region, China. *J. Geogr. Sci.* **2014**, *24*, 303–312. [CrossRef]
15. Fan, J.; Shao, Q.; Liu, J.; Wang, J.; Harris, W.; Chen, Z.; Zhong, H.; Xu, X.; Liu, R. Assessment of effects of climate change and grazing activity on grassland yield in the Three Rivers Headwaters Region of Qinghai-Tibet Plateau, China. *Environ. Monit. Assess.* **2010**, *170*, 571–584. [CrossRef]
16. Liu, Y.; Wang, Q.; Zhang, Z.; Tong, L.; Wang, Z.; Li, J. Grassland dynamics in responses to climate variation and human activities in China from 2000 to 2013. *Sci. Total Environ.* **2019**, *690*, 27–39. [CrossRef]
17. Xu, H.; Wang, X.; Zhang, X. Alpine grasslands response to climatic factors and anthropogenic activities on the Tibetan Plateau from 2000 to 2012. *Ecol. Eng.* **2016**, *92*, 251–259. [CrossRef]
18. Zhou, W.; Gang, C.; Zhou, F.; Li, J.; Dong, X.; Zhao, C. Quantitative assessment of the individual contribution of climate and human factors to desertification in northwest China using net primary productivity as an indicator. *Ecol. Indic.* **2015**, *48*, 560–569. [CrossRef]
19. Chen, B.; Zhang, X.; Tao, J.; Wu, J.; Wang, J.; Shi, P.; Zhang, Y.; Yu, C. The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. *Agric. For. Meteorol.* **2014**, *189–190*, 11–18. [CrossRef]
20. Zhang, Y.; Zhang, C.; Wang, Z.; Chen, Y.; Gang, C.; An, R.; Li, J. Vegetation dynamics and its driving forces from climate change and human activities in the Three-River Source Region, China from 1982 to 2012. *Sci. Total Environ.* **2016**, *563–564*, 210–220. [CrossRef]
21. Zhao, L.; Zhou, W.; Peng, Y.; Hu, Y.; Ma, T.; Xie, Y.; Wang, L.; Liu, J.; Liu, Z. A new AG-AGB estimation model based on MODIS and SRTM data in Qinghai Province, China. *Ecol. Indic.* **2021**, *133*, 108378. [CrossRef]
22. Wei, X.; Yan, C.; Wei, W. Grassland Dynamics and the Driving Factors Based on Net Primary Productivity in Qinghai Province, China. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 73. [CrossRef]
23. Wang, T.; Zhou, D.; Shen, X.; Fan, G.; Zhang, H. Koppen's climate classification map for China. *J. Meteorol. Sci.* **2020**, *40*, 752–760. (In Chinese)
24. Qinghai General Station of Grassland. *Qinghai Grassland Resources*; Qinghai People's Publishing House: Xining, China, 2012. (In Chinese)
25. Piao, S.; Fang, J.; He, J.; Xiao, Y. Spatial distribution of grassland biomass in China. *Acta Phytoecol. Sin.* **2004**, *28*, 491–498. (In Chinese)

26. Ge, J.; Meng, B.; Liang, T.; Feng, Q.; Gao, J.; Yang, S.; Huang, X.; Xie, H. Modeling alpine grassland cover based on MODIS data and support vector machine regression in the headwater region of the Huanghe River, China. *Remote Sens. Environ.* **2018**, *218*, 162–173. [CrossRef]
27. Zhou, G.; Zhang, X. Study on NPP of natural vegetation in China under global climate change. *Acta Phytoecol. Sin.* **1996**, *20*, 11–19. (In Chinese)
28. Zhu, W.; Pan, Y.; He, H.; Yu, D.; Hu, H. Simulation of maximum light use efficiency for some typical vegetation types in China. *Chin. Sci. Bull.* **2006**, *51*, 457–463. [CrossRef]
29. Wei, Y.; Wang, L.; Shi, Y.; Li, L. The study on simulating light use efficiency of vegetation in Qinghai Province. *Sci. Geogr. Sin.* **2012**, *32*, 621–627. (In Chinese)
30. Zhang, M.; Jiang, W.; Chen, Q.; Liu, X. Use improved CASA model to estimate the maximum light use efficiency of class in grassland comprehensive and sequential classification system. *Grassl. Turf* **2012**, *32*, 60–66. (In Chinese)
31. Dong, Y.; Yan, H.; Du, W.; Hu, Y. Spatio-temporal analysis of grassland carrying capacity in Mongolian Plateau based on supply-consumption relationship. *J. Nat. Resour.* **2019**, *34*, 1093–1107. (In Chinese) [CrossRef]
32. Shao, H.; Sun, X.; Wang, H.; Zhang, X.; Xiang, Z.; Tan, R.; Chen, X.; Xian, W.; Qi, J. A method to the impact assessment of the returning grazing land to grassland project on regional eco-environmental vulnerability. *Environ. Impact Assess. Rev.* **2016**, *56*, 155–167. [CrossRef]
33. Li, C.; Fu, B.; Wang, S.; Stringer, L.C.; Wang, Y.; Li, Z.; Liu, Y.; Zhou, W. Drivers and impacts of changes in China's drylands. *Nat. Rev. Earth Environ.* **2021**, *2*, 858–873. [CrossRef]
34. Yin, Y.; Hou, Y.; Langford, C.; Bai, H.; Hou, X. Herder stocking rate and household income under the Grassland Ecological Protection Award Policy in northern China. *Land Use Policy* **2019**, *82*, 120–129. [CrossRef]
35. Shao, Q.; Fan, J.; Liu, J.; Huang, L.; Cao, W.; Liu, L. Target-based Assessment on Effects of First-stage Ecological Conservation and Restoration Project in Three-river Source Region, China and Policy Recommendations. *Bull. Chin. Acad. Sci.* **2017**, *32*, 35–44. (In Chinese)
36. Wang, F.; Wei, X.; Ma, S. The study on forage yield and stocking rate of alpine meadow based on normalized difference vegetation index data. *Chin. J. Grassl.* **2021**, *43*, 78–85. (In Chinese)
37. 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]
38. Chen, H.; Ju, P.; Zhang, J.; Wang, Y.; Zhu, Q.; Yan, L.; Kang, X.; He, Y.; Zeng, Y.; Hao, Y.; et al. Attribution analyses of changes in alpine grasslands on the Qinghai-Tibetan Plateau. *Sci. Bull.* **2020**, *65*, 2406–2418. (In Chinese) [CrossRef]
39. Zhang, H.; Fan, J.; Wang, J.; Cao, W.; Harris, W. Spatial and temporal variability of grassland yield and its response to climate change and anthropogenic activities on the Tibetan Plateau from 1988 to 2013. *Ecol. Indic.* **2018**, *95*, 141–151. [CrossRef]
40. Gao, Y.; Zhou, X.; Wang, Q.; Wang, C.; Zhan, Z.; Chen, L.; Yan, J.; Qu, R. Vegetation net primary productivity and its response to climate change during 2001–2008 in the Tibetan Plateau. *Sci. Total Environ.* **2013**, *444*, 356–362. [CrossRef]
41. Wu, J.; Li, M.; Zhang, X.; Fiedler, S.; Gao, Q.; Zhou, Y.; Cao, W.; Hassan, W.; Margarint, M.C.; Tarolli, P.; et al. Disentangling climatic and anthropogenic contributions to nonlinear dynamics of alpine grassland productivity on the Qinghai-Tibetan Plateau. *J. Environ. Manag.* **2021**, *281*, 111875. [CrossRef]
42. Świąder, M.; Szewrański, S.; Kazak, J.K. Environmental Carrying Capacity Assessment—The Policy Instrument and Tool for Sustainable Spatial Management. *Front. Environ. Sci.* **2020**, *8*, 579838. [CrossRef]
43. Widodo, B.; Lupyanto, R.; Sulistiono, B.; Harjito, D.A.; Hamidin, J.; Hapsari, E.; Yasin, M.; Ellinda, C. Analysis of Environmental Carrying Capacity for the Development of Sustainable Settlement in Yogyakarta Urban Area. *Procedia Environ. Sci.* **2015**, *28*, 519–527. [CrossRef]