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Impacts of Climate Change and Anthropogenic Activities on the Net Primary Productivity of Grassland in the Southeast Tibetan Plateau

Yanmei Pang [1,2], Chao Chen [1,3,*], Bin Guo [4,*], Dongmei Qi [1] and Yu Luo [5]

[1] Institute of Plateau Meteorology, China Meteorological Administration, Chengdu/Heavy Rain and Drought-Flood Disasters in Plateau and Basin Key Laboratory of Sichuan Province, Chengdu 610072, China; pangyanm@126.com (Y.P.); qidongmei1983@163.com (D.Q.)
[2] Key Laboratory of Disaster Prevention and Mitigation of Qinghai Province, Xining 810001, China
[3] Provincial Key Laboratory of Water-Saving Agriculture in Hill Areas of Southern China, Chengdu 610066, China
[4] Aba Prefecture Meteorological Bureau, Maerkang 624000, China
[5] Sichuan Climate Center, Chengdu 610072, China; lda2008891229@163.com
* Correspondence: chenchao16306@sina.com (C.C.); abgb_001@163.com (B.G.)

Abstract: Climate change and anthropogenic activities have had a profound effect on the variation in grassland productivity in the Tibetan Plateau in recent decades. Quantifying the impacts of climatic and anthropogenic variables on grassland productivity is a necessary step in making the management policies of a sustainable grassland ecosystem. Net primary productivity (NPP) is an important part of the terrestrial carbon cycle and can be used to assess vegetation growth. Based on the Carnegie–Ames–Stanford Approach model and statistical analysis method, in this study we estimated the variations in grassland potential NPP (PNPP), actual NPP (ANPP) and human-induced NPP (HNPP) in the Northwest Sichuan Plateau (NWSP) of the Southeast Tibetan Plateau from 2001 to 2020. Also, we assessed the contribution of climatic change and anthropogenic activities to grassland ANPP. The results showed that the average values of grassland ANPP, PNPP and HNPP in the whole NWSP increased at the rates of 3.81, 9.14 and 7.18 g C m^{-2} a^{-1}, respectively. Grassland ANPP increased in 91.7% of the total area. Climate-oriented impacts led grassland ANPP to increase in 82.6% of the area, and temperature increase was the dominant factor. Additionally, anthropogenic activity was the major reason for the grassland ANPP's decline (5.4% of the total area). Overall, our findings are beneficial for the formulation of practical countermeasures regarding climate change adaption and damaged grassland recovering in the plateau.

Keywords: climate change; anthropogenic activity; net primary productivity (NPP); potential NPP; human-induced NPP; grassland; Southeast Tibetan Plateau; Northwest Sichuan Plateau

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1. Introduction

As the core issue of land degradation, the reduction in grassland productivity has become the research focus of global change and terrestrial ecosystems in the past few decades [1]. According to the survey of rangeland status in Chinese grassland provinces, grassland resources in China are seriously degraded. Although some measures have been taken in the past 20 years, the general trend of grassland degradation has not been reversed [2,3].

Climate change and anthropogenic activities dramatically alter ecosystem functions, structures and services. One of the most critical mechanisms for such changes is through the impacts on net primary productivity (NPP) and vegetation cover [4]. NPP is the accumulation of plant organic matter per unit time [5], which is an important section of the terrestrial carbon cycle and can act as an important indicator for assessing vegetation growth [6,7]. Therefore, the quantitative estimation of NPP on global and regional scales is critical for assessing carbon fixation and eco-behavior to obtain a better understanding of the variations in ecosystem function and structure [8]. In addition, studies on the changes in NPP and its influencing factors can increase our understanding of how ecosystems respond to anthropogenic activity and climate change. In particular, assessing the contributions of anthropogenic activities and climatic variations to NPP has become a hot topic of global concern [4].

Some researchers used various methods (e.g., partial derivative analysis, multi-variate analysis, principal component analysis and regression analysis) to quantitatively evaluate the impacts of climate change and anthropogenic activities on grassland NPP. These methods assume that a variation in vegetation is linearly related to climatic and anthropogenic factors and then utilize change trends or regression coefficients to evaluate the contribution of each influencing variable [9–12]. In recent years, a popular method has been used in some studies [4,12,13], which presumes that actual NPP (ANPP) is affected by both anthropogenic and climatic variables, while potential NPP (PNPP) is only affected by climatic change. Thus, the difference between PNPP and ANPP is described as the NPP affected by anthropogenic activities (HNPP). This method quantitatively assesses the driving variables of grassland variations and can exactly identify the effects of anthropogenic activities and climate change on grassland NPP [4].

The Northwest Sichuan Plateau (NWSP) is located in the southeast of the Tibet Plateau. It is a critical water source conservation region in the upper reaches of the Yellow River and the Yangtze River. Grasslands cover more than 60% of the NWSP. The NWSP is one of the major pasture regions in China with a high yield and good quality of forage grass [14]. Since 1961, there has been a significant warming trend in the NWSP [13]. Meanwhile, the significant increase in population and livestock number has also resulted in serious grassland degradation. The loss of plant diversity and reduction in vegetation cover were reported by numerous researchers. By the 2000s, approximately 56% of grasslands in the NWSP were degraded [13,15–17].

Previous studies reported that the grassland ecosystem is sensitive to climate change and anthropogenic activities [3,12,18,19]. The significant changes in environmental conditions and the increasing impacts of anthropogenic activities lead to grassland degradation, threatening the livelihoods of people in areas that are highly dependent on resources and the environment, such as the Tibetan plateau [6,16,20]. Various factors may also interact to indirectly or directly affect changes in grassland productivity over space and time. Moreover, changes in NPP and its drivers may be particularly significant in ecologically fragile areas. However, there is still a lack of an in-depth understanding about the effects of climate variations and anthropogenic activities on grassland ecosystems. Therefore, quantifying the effects of climatic variations and anthropogenic activities on grassland NPP is critical to deal with climate change and grassland management. In addition, in order to protect and restore grassland, a series of ecosystem conservation policies and ecological engineering projects were carried out by the government in various countries and regions. Taking China as an example, the program of "return grazing land to grassland" started in 2003, while the grassland ecological compensation policy started in 2009 [13]. However, it is still not clear how the implementation of ecosystem conservation policies under climate change affect variations in grassland productivity. The purposes of this paper are as follows: (1) analyzing the spatiotemporal changes in grassland ANPP, PNPP and HNPP during 2001–2020 over the NWSP; (2) exploring the relationships between climatic variables and grassland ANPP; (3) quantifying the effects of anthropogenic activities and climatic change on grassland ANPP. This study can provide some useful information for grassland management and sustainability.

2. Materials and Methods

2.1. Study Area

The NWSP is part of the Tibetan Plateau, covering the Aba Tibetan and Qiang Autonomous Prefecture and the Ganzi Tibetan Autonomous Prefecture (Figure 1). The terrain in the study area is complex. The elevation of most areas is above 3000 m [14]. There are various climate types, mainly including subtropical, warm temperate, middle temperate, cold temperate, subarctic, cold and permafrost zones. The general climatic characteristics are dry–warm river valleys, cold–wet mountains, abundant sunshine and less precipitation. In this area, there is the Ruoergai Prairie, one of the five major grasslands in China, as well as alpine grasslands and forests. The NWSP is an important forestry base and animal husbandry base and a vital ecological barrier in the upper reaches of the Yellow River and the Yangtze River in China [14].

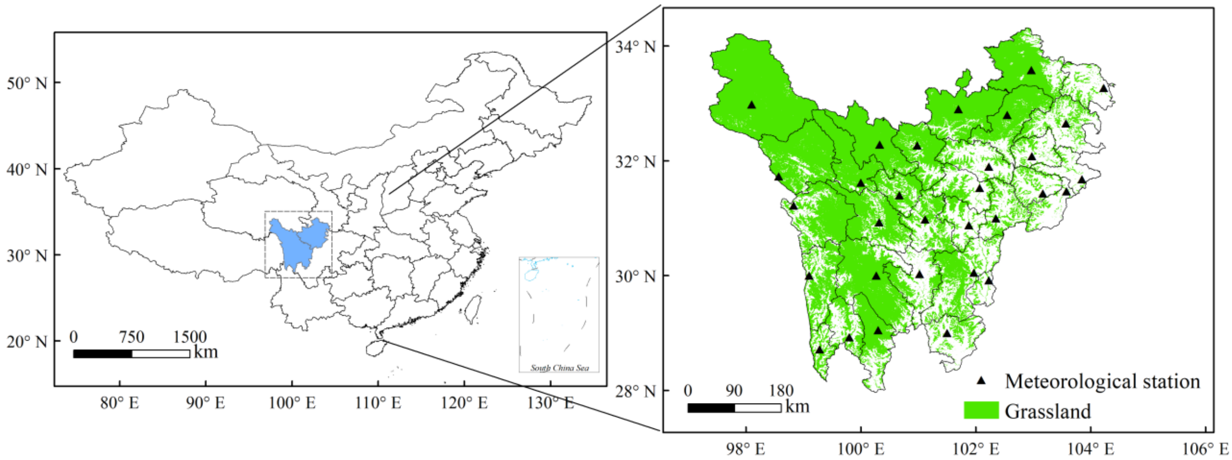

Figure 1. Spatial distribution of the meteorological stations in the study area.

2.2. Data Collection

The normalized difference vegetation index (NDVI) data (MOD13A2) with spatial and temporal resolutions of 250 m and 16 days were collected from the National Aeronautics and Space Administration (NASA) (http://reverb.echo.nasa.gov). Based on the MATLAB platform, combined with Savitzky–Golay filtering and quality control files, the NDVI data of MOD13A2 product was filtered and reconstructed. In addition, the main grassland type in the study area is alpine meadow, with a relatively uniform distribution. Generally, the biomass reached its maximum value in July. Therefore, the annual NDVI data were developed by utilizing the maximum value composition (MVC) method, which to some extent overcomes the issues of NDVI saturation effect and seasonal variations.

The monthly meteorological data during 2001–2020 were provided by the China Meteorological Data Network (http://data.cma.cn/). The variables included precipitation, sunshine duration and temperature. Temperature and precipitation data were collected from 31 weather stations. Solar radiation data were estimated with the observed sunshine duration from 31 weather stations by the Ångström–Prescott (A–P) equation [21] (Figure 1). These meteorological data were interpolated by the Kriging method to generate the grid image at a spatial resolution of 250 m [22].

Sheep and large livestock (cattle and horses) are included and transformed into standardized sheep units. The criteria are that one sheep is equal to one standardized sheep unit, and one large livestock is equal to four standardized sheep units.

The vegetation type and distribution data were obtained from the MODIS 16-day land cover product (MCD12Q1) provided by NASA (http://reverb.echo.nasa.gov). The numbers of livestock and population were from the Sichuan Statistical Yearbook from 2002 to 2021. Livestock includes large livestock (horses and cattle) and sheep. The criteria are that one sheep is equal to one standardized sheep unit, and one large livestock is equal to four standardized sheep units [13].

2.3. Methods

2.3.1. NPP Calculation

The Carnegie–Ames–Stanford Approach (CASA) combines satellite observation of the NDVI with climate variables such as precipitation, temperature and solar radiation [23]. The NDVI presents the land-use variation and the vegetation production appropriated by humans. Therefore, NPP simulated by CASA can be regarded as ANPP (g C m^{-2}) [13] (Equations (1)–(3)).

$$\text{ANPP} = \text{APAR} \times \varepsilon \tag{1}$$

$$\text{APAR} = \text{FPAR} \times \text{SOL} \times 0.5 \tag{2}$$

$$\varepsilon = T_{\text{high}} \times T_{\text{low}} \times W_{\varepsilon} \times \varepsilon_{\text{max}} \tag{3}$$

where APAR is the photosynthetically active radiation absorbed by vegetation (MJ m^{-2}). ε is light utilization efficiency of green vegetation (gC MJ^{-1}). FPAR is the photosynthetically active radiation rate of vegetation canopy. SOL is total solar radiation (MJ m^{-2}). T_{high} and T_{low} are the coefficients of effects of high temperature and low temperature on light utilization efficiency, respectively. W_{ε} is the coefficient of effect of water stress on light utilization efficiency; ε_{max} is the maximum value of light utilization efficiency and is set to 0.542 g C MJ^{-1} in this paper [12,24].

The Thornthwaite memorial model [25] is widely used in calculating PNPP (g C m^{-2}) [4,26]. PNPP is simulated by this model using precipitation and temperature data. The equations can be expressed as Equations (4)–(6).

$$\text{PNPP} = 3000\left[1 - e^{-0.0009695(av-20)}\right] \tag{4}$$

$$av = \frac{1.05p}{\sqrt{1 + (1 + \frac{1.05p}{mv})^2}} \tag{5}$$

$$mv = 3000 + 25t + 0.05t^3 \tag{6}$$

where av and mv are the annual actual evapotranspiration (mm) and the annual mean evapotranspiration (mm), respectively. t and p are the annual mean air temperature (°C) and annual precipitation (mm), respectively [4].

HNPP represents the effect of anthropogenic activities on grassland NPP, reflecting the loss of NPP [4]. HNPP (g C m^{-2}) can be calculated by Equation (7).

$$\text{HNPP} = \text{PNPP} - \text{ANPP} \tag{7}$$

2.3.2. Validation of ANPP Estimation

A field survey dataset in the summers (July and August) from 2006 to 2020 in the NWSP was collected to validate the ANPP calculated by CASA model. The collected dataset included the aboveground biomass and belowground biomass at 6 grassland monitoring stations over the NWSP. For all sites, three plots (1 m × 1 m) were selected, with the distance between plots being more than 250 m. To obtain the actual biomass, all aboveground plants and roots in the three plots were harvested to measure the weight. Further details of the sampling methods can be found in other literature [27,28]. The biomass data were converted to ANPP based on the previous method [6,29]. The correlation between observed ANPP and simulated ANPP was utilized to validate the result. As shown in Figure 2, simulated ANPP matched well with observed ANPP (R^2 = 0.51, $p < 0.01$).

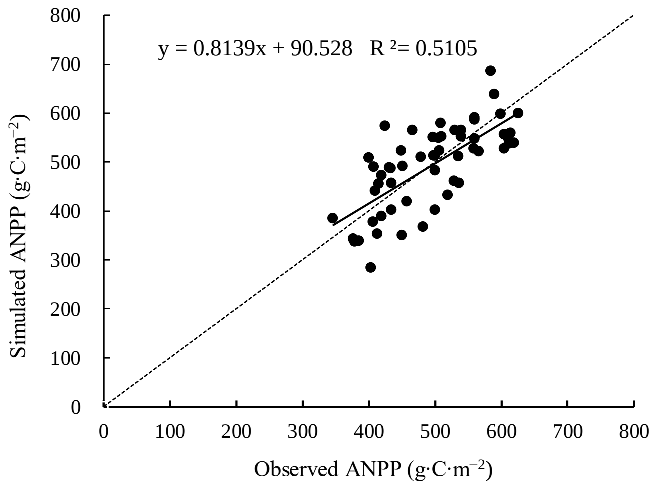

Figure 2. Comparison between simulated and observed grassland ANPP in the NWSP.

2.3.3. Trend Analysis

The linear regression equation based on the least square method was utilized to describe the change trend of the variable over the NWSP during 2001–2020 [30], as shown in Equation (8).

$$Q_{\text{slope}} = \frac{n\sum_{i=1}^{n} ix_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} x_i}{n\sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{8}$$

where Q_{slope} is the change trend of the variable, n is the length of time, and x_i is the variable value in the ith year. The F-test method was utilized to test the significance of change trend. A positive Q_{slope} indicates an increasing trend in the variable, while a negative Q_{slope} indicates a decreasing trend in the variable.

As for PNPP, a positive slope means that climatic change is beneficial to grassland productivity. However, a negative slope indicates climatic change is detrimental to grassland productivity. A positive slope for HNPP means that anthropogenic activities is detrimental to grassland growth, whereas a negative slope indicates that anthropogenic activities promote grassland growth. In this study, different scenarios are defined in Table 1 to explain the reasons for ANPP variation [4,9].

Table 1. Six scenarios of ANPP variation in the NWSP.

Q_{slope}_ANPP	Q_{slope}_PNPP	Q_{slope}_HNPP	Reason for ANPP Variation
Q_{slope}_ANPP > 0	+	+	Climatic change induced an ANPP increase (AIC)
	−	−	Anthropogenic activities induced an ANPP increase (AIH)
	+	−	Both climatic change and anthropogenic activities induced an ANPP increase (AICH)
Q_{slope}_ANPP < 0	−	−	Climatic change induced an ANPP decrease (ADC)
	+	+	Anthropogenic activities induced an ANPP decrease (ADH)
	−	+	Both climatic change and anthropogenic activities induced an ANPP decrease (ADCH)

Q_{slope}_PNPP, Q_{slope}_ANPP and Q_{slope}_HNPP are the slopes of PNPP, ANPP and HNPP variations, respectively.

2.3.4. Correlation Analysis

To analyze the relationships between climatic variables and vegetation productivity, correlation analysis was used in this study [19,31]. The formula is as follows (Equation (9)):

$$R_{xy} = \frac{\sum_{i=1}^{n}\left[(x_i - \overline{x})(y_i - \overline{y})\right]}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{9}$$

where R_{xy} is the correlation coefficient between variables x and y. x_i and y_i indicate the variables x and y in ith year, respectively. $\overline{x}$ and $\overline{y}$ denote the multi-year average of x and y, respectively. n is the number of study years. Additionally, the t-test method is utilized to test the significance of R_{xy}, and $p < 0.05$ is considered statistically significant [19].

3. Results

3.1. Spatiotemporal Variations of Grassland NPP in the NWSP

The annual grassland ANPP, PNPP and HNPP in the NWSP showed upward trends from 2001 to 2020. Annual grassland PNPP significantly increased with a value of 9.14 g C m^{-2} a^{-1} ($p < 0.05$) (Figure 3b), which was higher than that of annual grassland ANPP and HNPP. Annual grassland HNPP and ANPP increased, with values of 7.18 and 3.81 g C m^{-2} a^{-1} (Figure 3a,c), respectively. In addition, average annual grassland ANPP, PNPP and HNPP were 344.7, 979.1 and 584.0 g C m^{-2} a^{-1}, respectively. Mean annual total grassland ANPP was 49,875 Gg C a^{-1}, with an increasing rate of 551.33 Gg C a^{-1} over the NWSP.

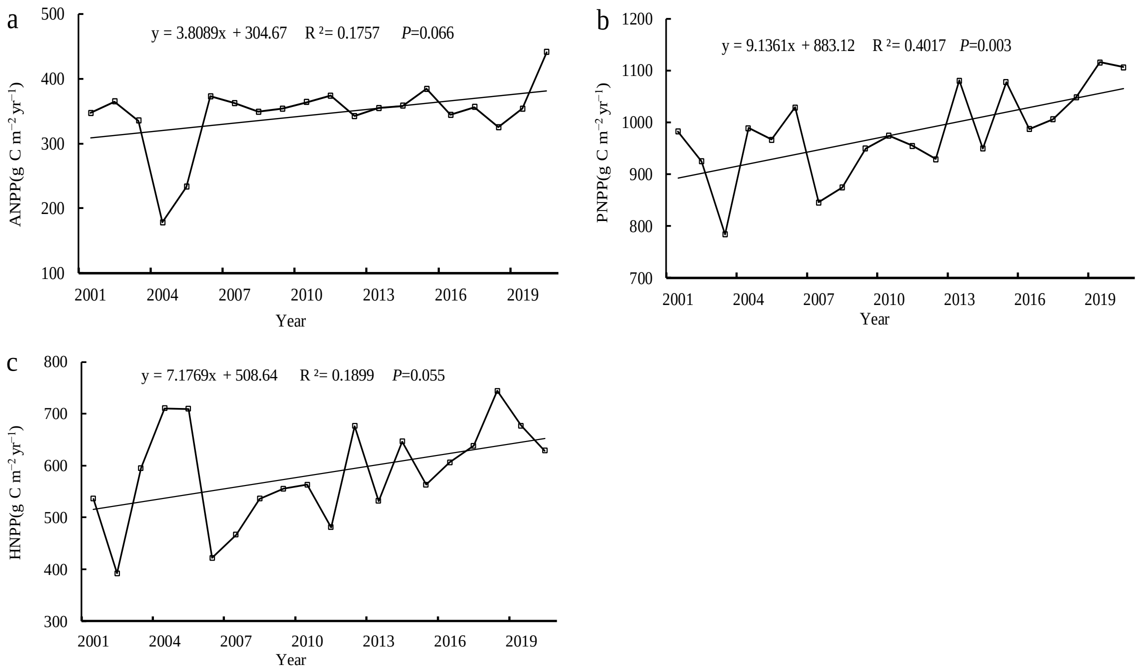

Figure 3. Inter-annual changes in (**a**) grassland ANPP, (**b**) grassland PNPP and (**c**) grassland HNPP in the NWSP during 2001–2020.

Under the impacts of anthropogenic activities and climatic change, grassland ANPP, PNPP and HNPP had obvious spatial heterogeneity (Figure 4). Alpine grassland was sensitive to precipitation and vulnerable to climate warming [32]. In this study, the spatial distribution characteristics between average annual grassland PNPP and average annual precipitation were similar, which indicated that precipitation was the major cause of PNPP variation. Specifically, mean annual PNPP increased from west to east during the past 20 years. The lowest values of PNPP (653–800 gC m^{-2}) were distributed in the southwest of the NWSP. The PNPP in the west and middle of the NWSP mostly ranged in 800–1030 g C m^{-2}. Additionally, the highest PNPP values (greater than 1030 gC m^{-2} a^{-1}) were distributed in the north and southeast of the NWSP (Figure 4b). As for HNPP, anthropogenic activities, such as overgrazing, transportation construction and urbanization in the plateau, had a direct effect on the spatial distribution of HNPP. The lowest HNPP values (lower than 500 g C m^{-2}) appeared in the southwest and northeast of the NWSP, while the highest values (more than 800 g C m^{-2}) were found in the central and southeast of the NWSP. The HNPP values in the remaining areas mostly ranged from 500 to 800 g C m^{-2}, showing a discrete geographical distribution (Figure 4c). Climate change and anthropogenic activities are unarguably two critical factors of vegetation dynamics. Therefore, ANPP change relates to PNPP and HNPP. In this study, higher PNPP values and lower HNPP values led to higher ANPP, while lower PNPP values and higher HNPP values were the main reason for lower ANPP. Specifically, the lowest ANPP values (lower than 200 g C m^{-2}) were in the east and west of the NWSP. On the contrary, the highest ANPP values (more than 500 g C m^{-2}) were distributed in the northeast of the NWSP. The ANPP values of the remaining areas (central and north of the NWSP) mostly ranged from 200 to 500 g C m^{-2} (Figure 4a).

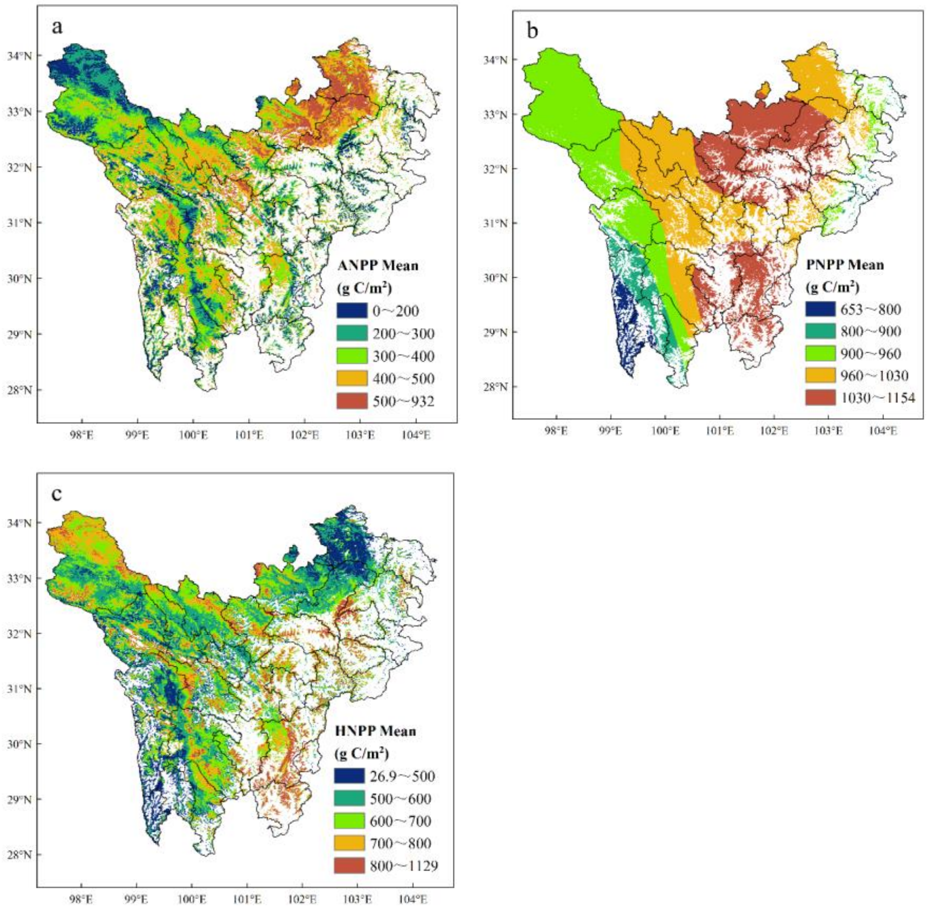

Figure 4. Spatial distributions of average annual (**a**) grassland ANPP, (**b**) grassland PNPP and (**c**) grassland HNPP in the NWSP during 2001–2020.

As shown in Figure 5, the area with an increasing trend for ANPP accounted for 91.7% of the total area, and 31.1% displayed a significant increase ($p < 0.05$), which is found in the southeast and north of the NWSP; climate change was the major cause for the increase in ANPP. However, ANPP showed a downward trend in some parts of the southwest (about 8.3%), and anthropogenic activity was the dominant driving factor for ANPP decrease (Figure 5a,d). The area with increased PNPP reached 93.6% of the total area, while the area with decreased PNPP was distributed in the southwest (only 6.4%). The PNPP in about 75.3% of the total area showed a significant increasing trend ($p < 0.05$), and these regions were located in the north and middle of the NWSP (Figure 5b,e). The spatial distribution characteristics between the variation trend of annual grassland PNPP (Figure 5b) and the variation trend of annual precipitation (Figure S1b) were similar, which indicated that the main driving force of the grassland PNPP change was precipitation. The HNPP in most areas experienced an increasing trend (89.2%). However, HNPP showed a decreasing trend in the south of the NWSP, which accounted for 10.8%. The HNPP in about 26.1% of the total area displayed a significant increase ($p < 0.05$), mainly distributed in the northeast and northwest of the NWSP (Figure 5c,f). During the past 20 years, although a series of ecosystem conservation policies and ecological engineering projects were carried out, the negative effects of anthropogenic activities on the alpine grassland ecosystem have still been intensifying, especially in the northern region of the NWSP.

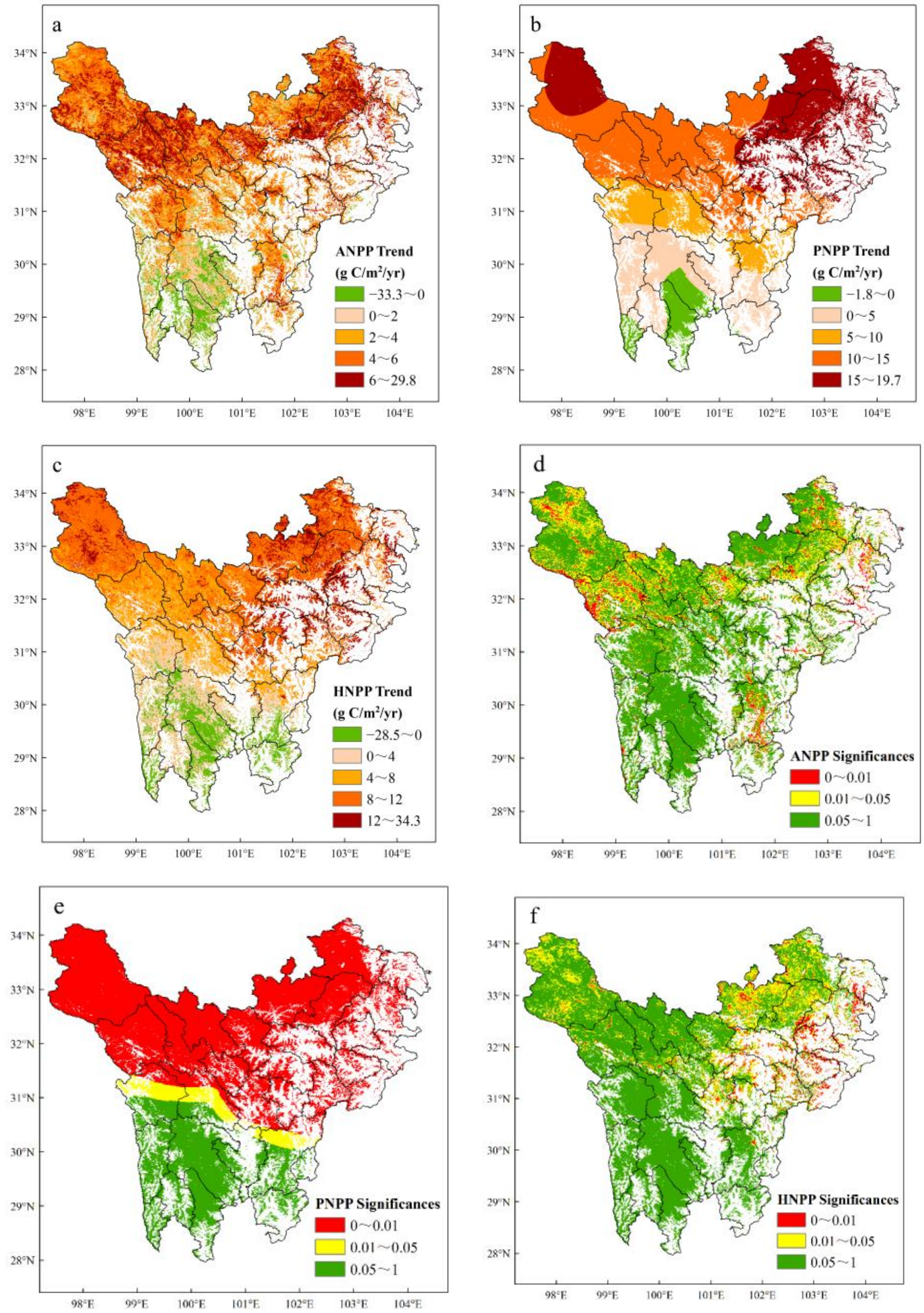

Figure 5. Spatial distributions of the variation trends and the corresponding significances of annual (**a**,**d**) grassland ANPP, (**b**,**e**) grassland PNPP and (**c**,**f**) grassland HNPP in the NWSP during 2001–2020.

3.2. Relationships between Climatic Variables and Grassland ANPP in the NWSP

As shown in Figure 6, the annual mean temperature and annual precipitation in the NWSP significantly increased, with values of 0.044 °C a^{-1} and 9.0 mm a^{-1} ($p < 0.05$), respectively (Figure 6a,b). However, the annual solar radiation significantly decreased, with a value of −18.19 MJ m^{-2} a^{-1} (Figure 6c). The spatial distributions of the variation trend and the corresponding significance of the climatic variables are displayed in Figure S1. The variation trends of the annual mean temperature ranged from −0.015 to

0.06 °C a^{-1}. The area with an increasing trend for the annual mean temperature accounted for 98.4% of the total area, and 90.6% displayed a significant increase ($p < 0.05$) (Figure S1a,d). The annual precipitation in most areas experienced an increasing trend (91.9%), and 75.5% displayed a significant increase ($p < 0.05$) (Figure S1b,e). The annual solar radiation showed a downward trend in some parts of the southwest, middle and north (about 58.9%), while the area with increased annual solar radiation reached 41.1%. The annual solar radiation in about 15.1% of the total area showed a significant variation trend ($p < 0.05$) (Figure S1c,f).

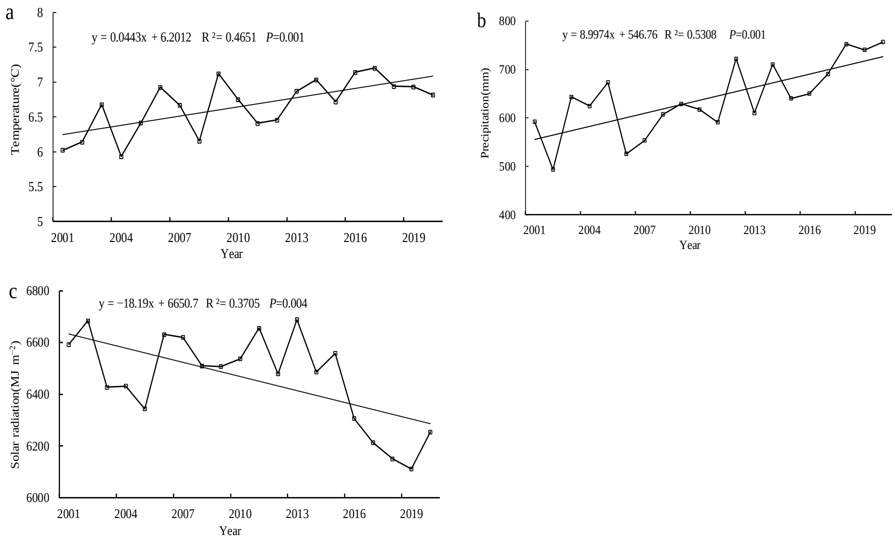

Figure 6. Variations of (**a**) annual mean temperature, (**b**) annual precipitation and (**c**) annual solar radiation in the NWSP during 2001–2020.

Correlation analysis was employed to evaluate the relationships between climatic variables (temperature, solar radiation and precipitation) and grassland ANPP in the NWSP (Figure 7). The temperature was positively correlated with ANPP in about 94.7% of the areas. The significantly positive relationships were located in the central and north of the NWSP (accounting for 18.4% of the total area; $p < 0.05$), demonstrating that the temperature increase in these regions was beneficial to the growth of ANPP. In contrast, the negative relationships between ANPP and temperature (with a proportion of 5.3%) implied that the temperature increase was detrimental to the growth of ANPP (Figures S1a and 7a), while the significantly negative relationships between ANPP and temperature only accounted for 0.2% of the total area ($p < 0.05$). Precipitation was positively correlated with ANPP in 48.2% of the total area, which was found in the northeast, southeast and northwest parts of the NWSP, indicating that the increase in precipitation was conducive to the growth of ANPP. In addition, the significantly positive relationships (accounting for about 1.7% of the total area; $p < 0.05$) implied that the increase in precipitation remarkably promoted grassland ANPP. Instead, the increase in precipitation exhibited inhibitory effects on the grassland ANPP in the rest of the NWSP, and the negative correlation coefficients accounted for 51.8% of the total area. The significantly negative relationships between ANPP and precipitation (accounting for 4.0% of the total area; $p < 0.05$) demonstrated that the increase in precipitation in these areas significantly went against the increase in ANPP (Figures S1b and 7b). In addition, solar radiation was positively correlated with ANPP in about 98.9% of the total area, implying that the decrease in solar radiation inhibited the grassland productivity in most areas of the NWSP. Moreover, the significantly positive relationships between ANPP and solar radiation in the west and northeast (accounting for 46.6% of the total area; $p < 0.05$) implied that the decrease in solar radiation had a significant inhibitory effect on grassland productivity over the NWSP. By contrary, the negative relationships between ANPP and solar radiation in the rest of the NWSP demonstrated that the decrease in solar radiation was conducive to grassland productivity (Figures S1c and 7c).

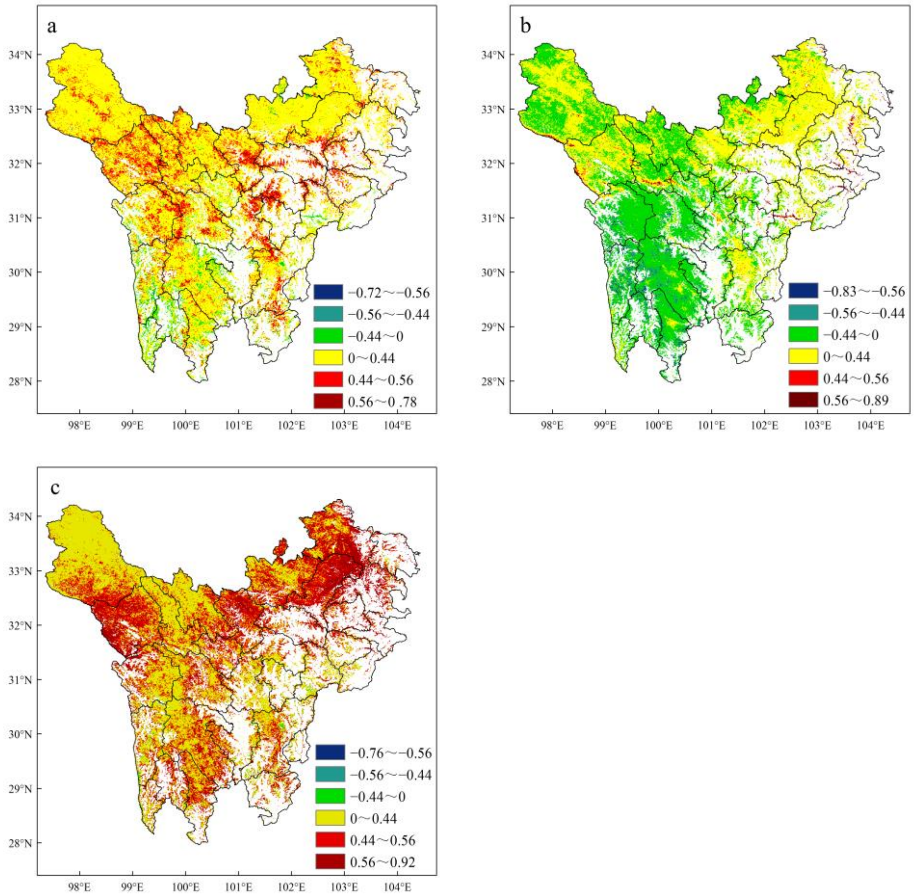

Figure 7. Spatial distributions of the correlation coefficients between grassland ANPP and (**a**) temperature, (**b**) precipitation and (**c**) solar radiation over the NWSP during 2001–2020. The values of 0.44 (−0.44) and 0.56 (−0.56) correspond to the 5% and 1% levels of significance.

3.3. Effects of Anthropogenic Activities and Climatic Change on Grassland ANPP in the NWSP

We investigated the effects of climate change and anthropogenic activities on grassland ANPP over the NWSP during 2001–2020 using the evaluation method defined in Table 1 (Figure 8 and Table 2). The grassland ANPP in about 91.7% of the total area showed an upward trend. Detailed analysis showed that the ANPP increase in 82.6% of the area was caused by climate change, followed by both climatic change and anthropogenic activities (6.0%) and anthropogenic activities (3.1%). The areas with a climate-induced increase in ANPP were found in the northern and central NWSP, while the anthropogenic-activities-induced and AICH-induced ANPP increases were distributed in some sections of the southwestern and southeastern NWSP.

Only about 8.3% of grassland areas showed a decrease in ANPP from 2001 to 2020. For the grassland ANPP decrease, anthropogenic activities played a key role and was the main driving factor (5.4% of the total area), followed by ADCH (1.8%) and climate change (1.1%), and this decreased ANPP was mainly located in some parts of the southwestern NWSP (Figure 8 and Table 2). Therefore, climate change was the dominant driving factor of the ANPP increase in most parts of the NWSP during 2001–2020, while anthropogenic activity was the major cause for the decrease in ANPP.

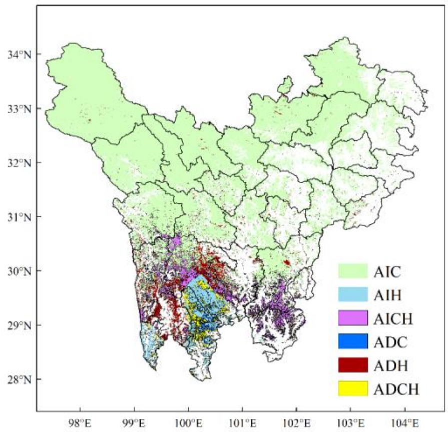

Figure 8. Spatial distributions of the relative contributions of anthropogenic activities and climatic change to the grassland ANPP variation over the NWSP during 2001–2020. AIC: climatic change induced an ANPP increase; AIH: anthropogenic activities induced an ANPP increase; AICH: both climatic change and anthropogenic activities induced an ANPP increase; ADC: climatic change induced an ANPP decline; ADH: anthropogenic activities induced an ANPP decline; ADCH: both climatic change and anthropogenic activities induced an ANPP decline. The same below.

Table 2. The percentage of grassland ANPP increase and decline caused by climate change, anthropogenic activities and their interaction in the NWSP during 2001–2020.

Grassland Restoration (%)			Grassland Degradation (%)		
AIC	**AIH**	**AICH**	**ADC**	**ADH**	**ADCH**
82.6	3.1	6.0	1.1	5.4	1.8

4. Discussion

4.1. Effects of Climatic Change on Grassland ANPP

Our study indicated that temperature, solar radiation and precipitation were the main climatic variables affecting vegetation dynamics, which agreed well with previous studies [6,19,30]. Generally, all climatic variables contribute to the variation in grassland ANPP. However, the effects of climatic variables on grassland ANPP are spatially heterogeneous. Temperature was positively correlated with ANPP in about 94.7% of the NWSP area (Figure 7a). Temperature was conducive to the increase in grassland ANPP in most of the study area, owing to the sensitivity of alpine grassland to the increasing temperature in the plateau climate zone [33]. The positive correlation between ANPP and solar radiation was found in 98.9% of the NWSP area (Figure 7c). The decrease in solar radiation is detrimental to grassland photosynthesis and contributes to ANPP decline [34]. In addition, precipitation was conducive to the increase in grassland ANPP in the northeast, northwest and southeast of the NWSP (accounting for about 48.2% of the total area) (Figure 7b), and this conclusion is consistent with previous studies [19,35]. However, precipitation was negatively correlated with ANPP in the rest of the NWSP (about 51.8% of the total area) (Figure 7b), which is consistent with other studies [36,37]. This may be due to the monsoon delivering sufficient rainfall. Nevertheless, the increase in precipitation is often accompanied by decreased solar radiation [38]. In addition, anaerobic soil conditions may occur in plant roots because of high soil water content that can inhibit vegetation growth [39].

Our study quantified the contributions of anthropogenic activities and climatic change to grassland productivity over the NWSP. The results are illustrated in Figure 8 and Table 2. By comparing with previous studies [19,40], we found that the relative contributions of climatic change to ANPP were greater in our study area than in other altitudinal zones. In about 82.6% of the total area, the contribution to the increased ANPP from 2001 to 2020 was from climate change, and related areas were distributed in most regions except the southwestern and southeastern NWSP. Therefore, the conclusion could be drawn that climatic change played the most important part in the increase in grassland ANPP in the NWSP. In addition, the warming and wetting trends over the NWSP were more intense in the past 20 years (0.044 °C a^{-1} and 9.0 mm a^{-1}) than in the past 60 years (0.023 °C a^{-1} and 1.3 mm a^{-1}), which could lead to the alpine grassland ecosystem becoming more vulnerable to climate change and more sensitive to grassland degradation caused by anthropogenic activities [9].

4.2. Effects of Anthropogenic Activities on Grassland ANPP

In this study, the result indicated that AIH and ADH were closely related to the changes in grassland ecosystem in the NWSP, which confirmed that anthropogenic activities were considered to be the key drivers of vegetation dynamics, and these drivers have mitigated or strengthened the change in vegetation productivity. The regions of human-induced grassland ANPP change accounted for 8.5% of the total grassland area from 2001 to 2020 (Figure 8 and Table 2), which is consistent with prior results [6,13]. In particular, in about 5.4% of the total area, the contribution to the decreased ANPP was from anthropogenic activities (Figure 8 and Table 2), which implies that anthropogenic activity was the main driving variable resulting in the decline of grassland ANPP in the NWSP.

Grazing is one of the main anthropogenic activities affecting grassland ANPP variations over the plateau. Especially, overgrazing is the major reason for grassland degradation in the region. In our study, the annual number of livestock over the NWSP during 2001–2020 was obtained to investigate the effects of grazing pressure on vegetation productivity. Livestock in the NWSP showed a significantly decreasing trend (Figure S2a) after the implementation of ecosystem conservation policies, which were launched by the Chinese government in 2000. Our results indicated that grassland ANPP increased at a rate of 3.81 g C m^{-2} a^{-1} (Figure 3a), and the ANPP increase of 3.1% in the area was caused by anthropogenic activities (Table 2). This implies that the implementation of ecological restoration policies has to be beneficial to the restoration of vegetation productivity in the NWSP, which is consistent with other studies in China [13,41]. Nevertheless, overgrazing is still one of the main causes for alpine grassland degradation, which could be seen from the annual livestock number (exceeding 1.9×10^7 heads) over the NWSP (Figure S2a).

Huge population growth and the rapid growth of the economy are the other variables causing grassland productivity variations. The population of the NWSP increased by 2.54×10^5 from 2001 to 2020 (Figure S2b). The increasing population and the improving quality of life caused an increase in food consumption (e.g., milk, meat and eggs), such that a decline in grassland productivity is the result of the anthropogenic appropriation of grassland ANPP [42]. Additionally, in recent years, many engineering projects (e.g., water conservancy and hydropower projects and airport construction) have been constructed, and tourism has also been continuously developed in the NWSP. Although the gross domestic product of the NWSP increased by CNY 75.458 billion from 2001 to 2020 (Figure S2c), natural resource development may have threatened the steppe ecology over the NWSP, thereby reducing grassland productivity [6]. Our results also suggest that anthropogenic activities were the major reason for the decline in grassland ANPP over the NWSP (Figure 8 and Table 2).

4.3. Methodological Considerations and Limitations

In this article, the HNPP, PNPP and ANPP were utilized to reveal the effects of anthropogenic activities and climatic change on grassland productivity over the NWSP. The simulation results of the CASA model were validated by contrasting the calculated and observed data of the grassland ANPP [4], and the comparison results suggest that the simulation was credible. Nevertheless, there are still uncertainties in this study. The short-term (20-year) changes in grassland productivity in our study region may indicate the effects of climatic change and anthropogenic activities, but the delay effect and short-term uncertainty inherent in climatic change and anthropogenic activities are difficult to avoid [4,43]. In addition, the meteorological data used in the study were obtained from the space interpolation of station observation data, which may also cause uncertainty regarding the conclusions [19]. In addition, our results in this article may ignore the effects of anthropogenic activities and climatic change owing to the large-scale spatial resolution, especially the effects of anthropogenic activities. Finally, prior studies showed that aboveground productivity is more sensitive to climate change than belowground productivity; thus, climate change may affect the proportion of aboveground and belowground ANPP [44]. However, these uncertainties may be decreased by utilizing localized simulation parameters and high-resolution remote sensing images in the future [4].

This method can be used to determine the effects of anthropogenic activities and climatic change on the average and trends of NPP in our study area. Nevertheless, the ecological effects of time variations in anthropogenic activities and climatic indexes are still inferior to those in previous research [4,45]. Recently, some studies on climate change underlined the correlations between slow variations in mean climatic indexes and amplified changes in climatic indexes [46]. Therefore, it is expected to include the interaction for an in-depth understanding of the ecological effects of anthropogenic activities and climatic change, particularly in the plateau region [4,47–50]. Additionally, this study could incorporate more indicators to evaluate the contributions of climate change and human activities to grassland ANPP in the future, such as the elasticity index, stability index and sensitivity index. This would consider the magnitude and direction of changes in PNPP, ANPP and HNPP, as well as the synergistic or antagonistic effects among the different influencing factors. Finally, various new methods based on machine learning were recently applied to such research, and these methods were demonstrated to be superior to our method in some aspects [51,52]. Anyway, our method is still the most extensively used approach at present for quantifying the impacts of anthropogenic activities and climatic change, due to the relatively simple operation and the easier data acquisition [19].

5. Conclusions

Using NPP as an indicator of grassland dynamics, this study revealed the effects of anthropogenic activities and climate change on grassland productivity in the NWSP, finding the different driving forces for grassland ANPP in the different study areas. A warming–wetting climate led to a significant increase in PNPP, which caused an increase in ANPP in most zones (82.6% of the total area) during 2001–2020. However, anthropogenic activities were the dominant factor for the increase in grassland ANPP in some zones (3.1% of the total area). This implies that improved anthropogenic activities (e.g., the return of grazing land to grassland and the obvious decrease in livestock number) in the NWSP in the last 20 years alleviated the grazing pressure of the rangeland and indirectly led to an ANPP increase. Therefore, regulatory constraints in rangeland planning and regulation should measure the response of community dynamics or the local population to human interferences. In addition, for precisely and fully separating the impacts of anthropogenic activities and climate change on the rangeland ecosystem, process-based ecosystem models and more field survey data are needed.

Briefly, although studies on the driving forces of grassland productivity variations over the NWSP are complex, our results offer a beneficial reference for the decisions and actions of the government department over the NWSP. In this way, effective management measures can be implemented to prevent grassland degradation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14081217/s1, Figure S1: Spatial distributions of the variation trends and the corresponding significances of (a,d) annual mean temperature, (b,e) annual precipitation, and (c,f) annual solar radiation in the NWSP during 2001–2020; Figure S2. Inter-annual variations of (a) total livestock number, (b) total population and (c) gross domestic product in the NWSP during 2001–2020.

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