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Growing Season Precipitation Rather than Growing Season Length Predominates Maximum Normalized Difference Vegetation Index in Alpine Grasslands on the Tibetan Plateau

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Abstract: Precipitation and growing season length (GSL) are vital abiotic and biotic variables in controlling vegetation productivity in alpine regions. However, their relative effects on vegetation productivity have not been fully understood. In this study, we examined the responses of the maximum normalized difference vegetation index (NDVImax) to growing season precipitation (GSP) and GSL from 2000 to 2013 in 36 alpine grassland sites on the Tibetan Plateau. Our results indicated that NDVImax showed a positive relationship with prolonged GSL (R^2 = 0.12) and GSP (R^2 = 0.39). The linear slope of NDVImax increased with that of GSP rather than GSL. Therefore, GSP had a stronger effect on NDVImax than did GSL in alpine grasslands on the Tibetan Plateau.

Keywords: growing season length; growing season precipitation; plant growth; alpine regions

1. Introduction

Growing season length (GSL) is a critical variable of vegetation phenology and also a vital aspect of biological systems [1–4]. Vegetation productivity plays important roles in ecosystem structure and function [5,6]. Warming and precipitation changes are important aspects of climatic changes. Many studies have indicated that climatic change can affect the start of the growing season and the end of the growing season, and in turn can lead to changes in GSL [7–10]. A few studies have examined the feedbacks of prolonged or delayed GSL on terrestrial ecosystems [3,8,11] and there are no consistent feedbacks. For example, there are positive [12], negative [13] or no effects [14] of prolonged GSL on vegetation productivity. Therefore, the feedbacks of prolonged GSL to vegetation productivity remain unclear.

Vegetation indices, such as the normalized difference vegetation index (NDVI), can reflect vegetation coverage and growth conditions [15,16]. Vegetation indices are often used to estimate aboveground biomass and vegetation productivity [17–19]. Growing season maximum aboveground plant biomass can be treated as aboveground net primary production in grassland ecosystems [6,20]. Growing season maximum NDVI (NDVImax) can be used to reflect aboveground net primary production in grassland ecosystems [21]. Previous studies have mainly focused on gross primary production, net primary production and net ecosystem production [12,22,23] rather than NDVImax. Therefore, it remains unclear how GSL changes will affect NDVImax.

Grasslands are important components of global terrestrial ecosystems [5,18,24] and the Tibetan Plateau is mainly covered by grasslands [25,26]. Although many studies have examined the responses of vegetation productivity to climatic change, only a few studies have investigated the effects of GSL changes on vegetation productivity [23,27,28]. No studies have investigated the responses of NDVImax to GSL change. Precipitation had a stronger effect on NDVImax than did temperature on the Tibetan Plateau [29] and shortened GSL was not correlated with gross primary production in an alpine meadow of the Northern Tibetan Plateau [27]. No studies have examined the relative effects of GSL and growing season precipitation (GSP) on NDVImax. Therefore, in this study, we analyzed the correlations of NDVImax with GSL and GSP. The main objective of this study was to compare the effects of GSP and GSL on NDVImax in alpine grasslands on the Tibetan Plateau.

2. Materials and Methods

2.1. Study Area

The Qinghai–Tibet Plateau is an important ecological security barrier in China. The average annual precipitation was 372 mm and the annual mean air temperature was 9.71 °C from 2000 to 2013 according to the China Meteorological Data Sharing Service System. The main vegetation types on the Qinghai–Tibet Plateau are alpine meadows, alpine grasslands and desert grasslands.

2.2. MOD13A2 and Phenological Metrics

Moderate resolution imaging spectroradiometer (MODIS) Collection 6 vegetation indices data (MOD13A2 with a spatial resolution of 1 km × 1 km and a temporal resolution of 16 days) were used in the current study. Images from 2000–2013 were used for this study. The Timesat–SG method was used to estimate the start of the growing season (SGS), the end of the growing season (EGS) and the growing season length (GSL) [30]. In this study, 20% and 50% was used as the two dynamic thresholds to determine SGS and EGS, respectively [23,30]. The maximum NDVI was labeled by NDVImax.

2.3. Climatic Data

Growing season precipitation (GSP), air temperature (T_a), ≥5 °C accumulated temperature (AccT) and the ratio of GSP to AccT (GSP/AccT) of 36 meteorological stations (Figure 1) were obtained from the China Meteorological Data Sharing Service System [31,32]. The GSP/AccT is a synthesized factor of air temperature and precipitation [33,34]. The UV-B radiation was high on the Tibetan Plateau (Fu & Shen, 2017).

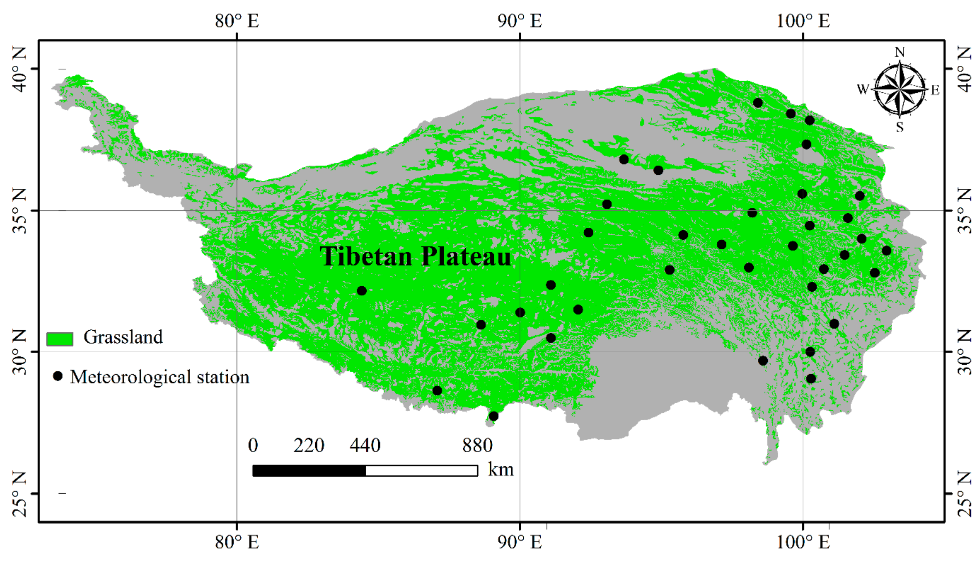

Figure 1. Locations of sampling sites in alpine grasslands on the Tibetan Plateau.

2.4. Statistical Analysis

Linear regressions of NDVImax with SGS, EGS, GSL, GSP, T_a, AccT and GSP/AccT were performed using all the data. Correlation coefficients of NDVImax with SGS, EGS, GSL, GSP, T_a, AccT and GSP/AccT were conducted for each site. Linear regression coefficients (i.e. slope) between NDVImax, SGS, EGS, GSL, GSP, T_a, AccT, GSP/AccT, and time series (i.e. from 2000 to 2013) were conducted to obtain the changes of these concerned parameters during 2000–2013 for all the 36 sites. The changes of NDVImax, SGS, EGS, GSL, GSP, T_a, AccT and GSP/AccT were labeled by slope_NDVImax, slope_SGS, slope_EGS, slope_GSL, slope_GSP, slope_T_a, slope_AccT and slope_GSP/AccT, respectively. Simple linear regressions and a multiple stepwise linear regression of slope_NDVImax with slope_SGS, slope_EGS, slope_GSL, slope_GSP, slope_T_a, slope_AccT and slope_GSP/AccT were performed.

$$slope = \frac{\sum_{i=2000}^{2012}(i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum_{i=2000}^{2012}(i-\overline{x})^2\sum_{i=2000}^{2012}(y_i-\overline{y})^2}}, \tag{1}$$

where i is the time series from 2000 to 2013; $\overline{x}$ is mean value from 2000 to 2013; y_i is the value of the concerned variables in the i year, and $\overline{y}$ is the mean value of the concerned variables from 2000 to 2013.

3. Results

3.1. Changes of GSP, T_a, AccT, GSP/AccT, SGS, EGS, GSL and NDVImax

Changes of GSP, T_a, AccT and GSP/AccT during 2000–2013 varied with meteorological stations (Table 1). GSP decreased by −15.23 to −0.14 mm a^{-1} in seven stations, but increased by 0.90–13.27 mm a^{-1} in the other 29 stations. T_a decreased by −0.07 to −0.01 °Ca^{-1} in seven stations, but increased by 0.02–0.11 °Ca^{-1} in the other 29 stations. AccT showed an increasing trend in most stations. GSP/AccT decreased by −0.01 to −0.00 mm °C^{-1} a^{-1} in 14 stations, but increased by 0.00–0.02 mm °C^{-1} a^{-1} in the other 22 stations.

Table 1. Linear change trends of growing season precipitation (GSP), air temperature (T_a), ≥5 °C accumulated air temperature (AccT), the ratio of GSP to AccT (GSP/AccT), start of growing season (SGS), end of growing season (EGS), growing season length (GSL) and maximum normalized difference vegetation index (NDVImax) during 2000–2013.

No	slope AccT (°C a^{-1})	slope GSP (mm a^{-1})	slope T_a (°C a^{-1})	slope GSP/AccT (mm °C $^{-1}$ a^{-1})	slope SGS (d a^{-1})	slope EGS (d a^{-1})	slope GSL (d a^{-1})	slope NDVImax (a^{-1})
52633	3.66	3.12	0.02	0.00	0.13	0.24	0.11	0.007
52645	6.94	7.91	0.03	0.01	−0.91	−0.34	0.57	−0.002
52657	21.23	5.55	−0.03	0.00	−1.36	0.64	2.00	0.005
52707	38.18	1.72	−0.07	0.00	−2.53	0.57	3.10	0.007
52754	15.82	3.24	−0.02	0.00	−1.27	0.98	2.25	−0.005
52818	2.99	0.90	0.03	0.00	−0.14	−0.34	−0.20	0.002
52908	5.90	7.46	−0.06	0.02	−1.07	1.55	2.61	0.001
52943	−5.28	4.20	0.06	0.00	0.37	−0.79	−1.16	−0.002
52974	15.66	6.94	0.02	0.00	−0.50	0.35	0.85	−0.001
55248	3.78	1.65	0.05	0.00	0.15	0.03	−0.12	−0.002
55279	4.65	4.47	0.02	0.00	−0.05	0.42	0.47	0.003
55294	2.02	−0.14	0.07	0.00	−1.59	−1.83	−0.24	−0.001
55299	4.31	−4.74	−0.01	−0.01	0.61	1.38	0.77	−0.004
55472	2.60	−1.14	0.05	0.00	0.88	0.32	−0.55	0.011
55493	8.81	−15.23	0.10	−0.01	0.83	0.18	−0.65	−0.003
55664	17.48	2.85	−0.04	0.00	0.29	1.41	1.11	0.002
55773	−5.60	1.29	0.05	0.00	1.54	−0.69	−2.23	0.004
56004	11.92	3.76	0.03	0.00	−0.97	−0.83	0.14	0.001
56018	11.96	3.59	0.02	0.00	−0.12	1.15	1.26	0.000
56021	16.08	12.69	0.03	0.01	−1.94	−0.20	1.74	0.009
56033	9.25	7.34	0.04	0.01	−1.70	−0.67	1.02	0.002
56034	14.25	12.91	0.06	0.01	−0.97	−0.20	0.77	0.000
56038	12.72	5.97	0.11	0.00	0.10	−0.32	−0.42	0.001
56043	9.49	8.15	0.10	0.00	0.38	−0.40	−0.78	0.006
56046	12.92	9.03	0.04	0.00	−0.85	0.22	1.07	0.005
56065	14.07	13.27	0.03	0.01	−0.81	0.81	1.62	−0.003
56067	8.14	5.53	0.07	0.00	−0.43	−0.84	−0.40	−0.001
56074	16.64	1.56	0.03	0.00	−0.63	0.70	1.32	0.004
56079	21.40	11.00	0.09	0.00	−1.18	−0.32	0.86	0.003
56151	8.54	6.06	0.05	0.00	−0.60	−0.41	0.19	−0.006
56152	9.34	3.72	0.05	0.00	−0.12	0.19	0.31	0.002
56167	45.48	4.05	−0.04	0.00	−2.26	1.62	3.89	0.003
56173	13.26	9.78	0.09	0.00	−0.73	−0.79	−0.06	0.003
56257	9.43	−12.75	0.05	−0.01	1.34	1.11	−0.23	−0.007
56342	5.16	−8.01	0.05	−0.01	−0.07	−0.07	0.00	−0.009
56357	28.75	−9.48	0.05	−0.01	−1.08	0.79	1.87	−0.004

Changes of SGS, EGS, GSL and NDVImax during 2000–2013 varied with meteorological stations (Table 1). SGS decreased by −2.53 to −0.05 day a^{-1} in 25 stations, but increased by 0.10–1.54 day a^{-1} in the other 11 stations. EGS decreased by −1.83 to −0.07 day a^{-1} in 16 stations, but increased by 0.03–1.62 day a^{-1} in the other 20 stations. GSL decreased by −2.23 to −0.06 day a^{-1} in 12 stations, but increased by 0.00–3.89 day a^{-1} in the other 24 stations. NDVImax in 16 sites showed decreasing trends by −0.01 to −0.00 a^{-1}, while that in the other 20 sites showed increasing trends by 0.00–0.01a^{-1}. "a" is annual.

3.2. Relationships between NDVImax and Phenological and Climatic Variables

The NDVImax increased significantly with GSP, GSP/AccT and GSL, but decreased significantly with SGS (Figure 2). The GSP, GSP/AccT, SGS and GSL explained significantly 39%, 8%, 21% and 12% variations of NDVImax, respectively (Figure 2). Multiple stepwise linear regressions between NDVImax and the concerned variables indicated that GSP and SGS together explained a 43.8% variation of NDVImax; and the GSP and SGS explained 39.3% and 4.4% variations of NDVImax, respectively. That is, the variations of NDVImax were more explained by GSP rather than SGS and GSL.

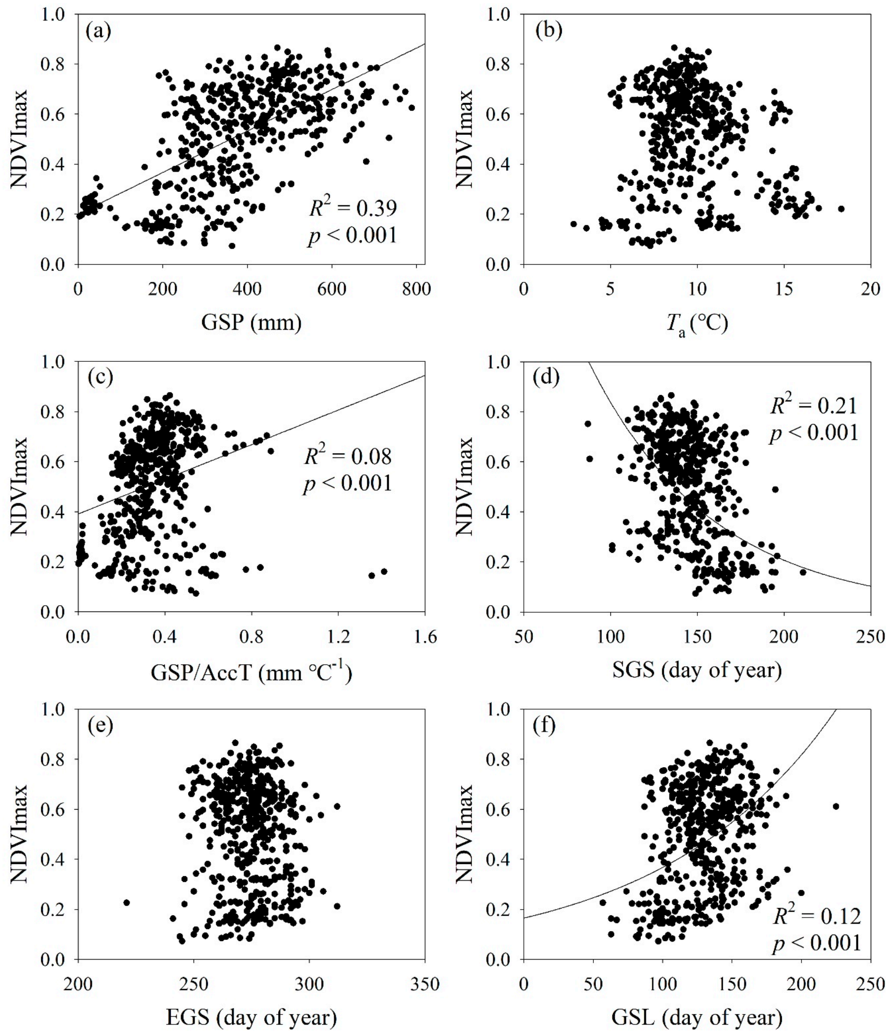

Figure 2. Relationships (**a**) between maximum normalized difference vegetation index (NDVImax) and growing season precipitation (GSP), (**b**) between NDVImax and growing season average air temperature (Ta), (**c**) between NDVImax and the ratio of GSP to accumulated temperature (GSP/AccT), (**d**) between NDVImax and start of growing season (SGS), (**e**) between NDVImax and end of growing season (EGS) and (**f**) between NDVImax and length of growing season (GSL).

Slope_NDVImax increased significantly with increasing slope_GSP and slope_GSP/AccT (Figure 3). Multiple stepwise linear regressions between slope_NDVImax and the changes of the concerned variables indicated that only slope_GSP was included in the regression equation. That is, the changes of NDVImax were obviously correlated with changes of climatic variables rather than those of phenological variables across all the 36 sites.

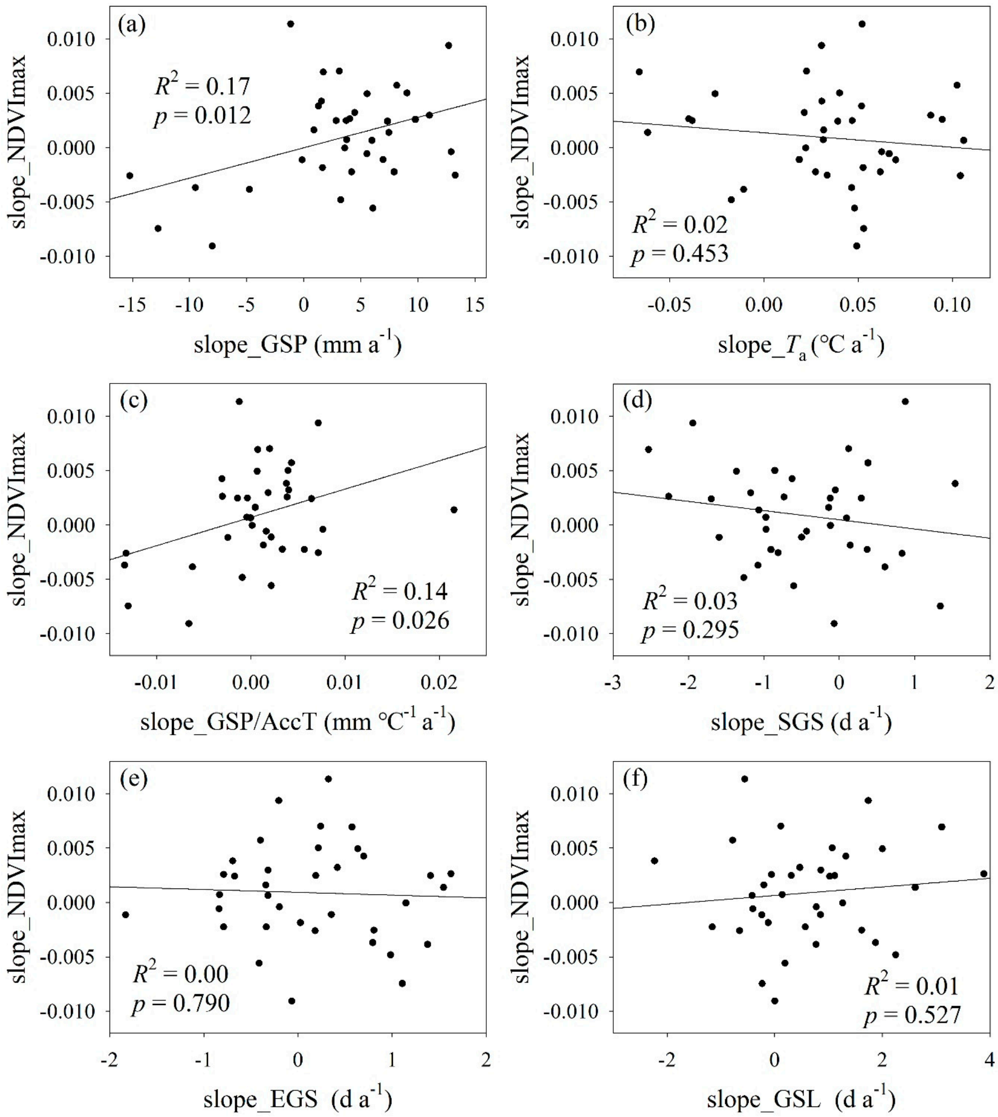

Figure 3. Relationships (**a**) between linear slope of maximum normalized difference vegetation index (slope_NDVImax) and that growing season precipitation (slope_GSP), (**b**) between slope_NDVImax and that of growing season average air temperature (slope_Ta), (**c**) between slope_NDVImax and that of the ratio of GSP to accumulated temperature (slope_ GSP/AccT), (**d**) between slope_NDVImax and that of the start of the growing season (slope_SGS), (**e**) between slope NDVImax and that of the end of the growing season (slope_EGS) and (**f**) between slope NDVImax and that of length of growing season (slope_GSL).

4. Discussion

4.1. *Effect of Climate Change*

Our findings implied that NDVImax could increase with increasing precipitation (Figure 2). Likewise, NDVImax showed a significant positive correlation with precipitation from 1982 to 2006 across the Tibetan Plateau [29]. NDVI increased with increasing precipitation from 1982 to 2000 in the three-river-source region on the Tibetan Plateau [35]. NDVI also showed a positive relationship with precipitation from 1985 to 1999 in the Lhasa area in the Tibetan plateau [36]. NDVI also increased with increasing precipitation from 1998 to 2007 in the Lake Yamzho Yumco Basin in the Tibetan Plateau [37]. These findings suggested that future climate change would most likely increase vegetation coverage and productivity considering that precipitation will increase in the 21st century for most areas on the Tibetan Plateau [38].

Change magnitudes of NDVImax were positively correlated with those of precipitation (Figure 3). Previous studies also indicated that change trends of NDVImax and growing season maximum enhanced vegetation index were positively correlated with those of precipitation from 2000 to 2012 across the Tibetan Plateau [15,21]. These findings implied that responses of alpine vegetation coverage and productivity to precipitation changes could be dependent on change magnitudes of precipitation. This was attributed to the fact that a higher magnitude of increased precipitation can result in a greater magnitude of soil moisture [39] and vegetation productivity can increase with increasing soil moisture in alpine grasslands on the Tibetan Plateau [40].

4.2. *Effects of GSL on NDVImax*

Our findings suggested that prolonged GSL could increase NDVImax across all the years and stations (Figure 2). This finding was in line with several previous studies [22,41]. For example, GSL had a positive effect on aboveground net primary production across several high elevation meadows in the USA and Asia [2].

Our findings also indicated that the relationships between NDVImax and GSL varied among stations (Table 1). This finding was also in line with previous studies [2]. A prolonged GSL did not increase net carbon uptake in the northeastern Siberian tundra [11], aboveground net primary production in an alpine snowbed [42] and gross primary production in a semi-arid grassland [14]. By contrast, a longer GSL increased aboveground plant biomass in a USA tallgrass prairie [1] and net ecosystem productivity in an alpine swamp meadow of the Northern Tibetan Plateau [43]. These diverse responses of vegetation productivity to GSL could be attributed to the following mechanisms. The net effects of GSL on vegetation productivity are determined by their relative strengths of beneficial and detrimental effects [14,42]. First, longer GSL caused by advanced SGS may result in earlier snowmelt [13] and potential detrimental effects of early frosts [42], which in turn can alter vegetation productivity. Second, longer GSL can increase GSP, which in turn can increase soil moisture and decrease vapor pressure deficit [44]. Vegetation productivity increases with increasing soil moisture and decreasing vapor pressure deficit [15,44].

4.3. *Stronger Effect of GSP on NDVImax than that of GSL*

In this study, we found that GSP rather than GSL predominated NDVImax variations across all the stations. This was in line with several previous studies [14,27]. For example, positive effects of premature phenological stages on carbon gain may be reduced by summer drought in the Tharandt forest [45]. These results suggest that the effects of GSL on vegetation productivity were dependent on precipitation in alpine grasslands on the Tibetan Plateau.

5. Conclusions

In this study, we compared the effects of GSP and satellite-derived GSL on NDVImax in alpine grasslands on the Tibetan Plateau. GSL and SGS explained 12% and 21% variations of NDVImax, respectively, while GSP explained a 39% variation of NDVImax. The linear slope of NDVImax showed a positive relationship with that of GSP, but did not correlate to that of GSL and SGS. Therefore, GSP rather than GSL controlled the variation of NDVImax.

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

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