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## RESEARCH ARTICLE

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### Key Points:

- Extreme heat and drought caused obvious drop in photosynthesis during August–September (AS) in 2022 in the Tibetan Plateau
- Warm early summer compensated reduction in photosynthesis in late summer
- Photosynthesis anomaly was temperature-driven in May–June–July, shifting to soil water control in AS

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## Warm Early Summer Compensated Reduction in Photosynthesis Caused by 2022 Late Summer Extreme Drought Over the Tibetan Plateau

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**Abstract** The Tibetan Plateau (TP) is ecologically delicate, its vegetation highly sensitive to climate variations. In 2022, China endured an unprecedented compound drought-heatwave, escalating TP's August temperature to a record high since 2000. This study examined this event's impact on TP's photosynthesis using multi-source satellite-based products. We demonstrated persistent high temperatures from April to August 2022, accompanied by shifting soil water (SW). Initially moist from April to June, the soil turned notably dry, hitting its lowest point in August. Consequently, early summer witnessed a substantial enhancement in gross primary productivity (GPP) and near-infrared reflectance of vegetation (NIRv) predominantly due to high temperatures, except for reduction in the eastern and southeastern TP. June recorded the largest positive GPP anomaly since 2000. As summer progressed, severe drought, not high temperatures, dominated, causing obvious negative anomalies in GPP and NIRv, especially in August, concentrated in the central and southwestern TP. Separating the growing season into May–June–July (MJJ) and August–September (AS) revealed a clear contrast. Enhancement in photosynthesis during MJJ compensated the decline in AS, making average positive GPP and weak negative NIRv anomalies in the entire growing season. Specifically, MJJ saw GPP magnitudes of 5.724 TgC mo<sup>-1</sup> in FluxSat, 9.491 TgC mo<sup>-1</sup> in GPP v2.2 and OCO-2-based Solar-induced chlorophyll fluorescence (GOSIF), and 0.004 in NIRv. Conversely, AS experienced a decline: -4.802 TgC mo<sup>-1</sup> in FluxSat, -2.837 TgC mo<sup>-1</sup> in GOSIF GPP, and -0.006 in NIRv. This delicate balance underscores the intricate interplay between early growth conditions, subsequent environmental stressors, and vegetation's adaptive responses.

**Plain Language Summary** In 2022, an extreme heat and dry event hit the ecologically fragile Tibetan Plateau (TP) in China. We used satellite data to analyze its impact. From April to August, the TP faced prolonged high temperatures, coupled with shifting soil water. Initially moist in April–June, the soil dried drastically, reaching its lowest in August. Early summer witnessed a substantial enhancement in vegetation photosynthesis, mainly due to high temperatures. However, as summer progressed, severe drought took hold, leading to decreased plant productivity, particularly in August, especially in the central and southwestern TP. By dividing the growing season into two periods (May–June–July [MJJ] and August–September [AS]), we found that photosynthesis during MJJ compensated for the later decline in AS, causing an overall positive GPP and a mild negative near-infrared reflectance of vegetation throughout the growing season. This study highlights the delicate balance between early growth conditions, subsequent environmental pressures, and plants' adaptive responses in the TP.

## 1. Introduction

In recent years, the frequency and intensity of extreme events such as droughts and heatwaves have been on the rise, accompanied by longer durations and wider geographical impact (Dai, 2012; Trenberth et al., 2013; P. Wang et al., 2017). Droughts and heatwaves have been widely recognized as one of the most important abiotic stresses affecting the terrestrial carbon cycle (Ciais et al., 2005; Perkins et al., 2012; Zscheischler et al., 2014). The Amazonian forests experienced two severe droughts in 2005 and 2010, both leading to substantial carbon emissions and potentially influencing climate change through feedbacks (Lewis et al., 2011; Phillips Oliver et al., 2009). Moreover, vegetation photosynthesis can be significantly inhibited under extremely high temperatures, and respiration may also decrease, causing ecosystems to shift from carbon sinks to carbon sources (Bastos et al., 2014; Chen

et al., 2023; Salvucci & Crafts-Brandner, 2004). However, the combined effect of high temperatures and drought on vegetation surpasses the individual effects of either high temperatures or drought alone, showing a nonlinear superposition of the two extremes (X. Zhu et al., 2021).

Gross primary productivity (GPP) is the largest carbon flux, changes of which affect the whole terrestrial carbon cycle (Chen et al., 2019). Due to more frequent droughts and heatwaves, a discernible increase of approximately 10.6% in GPP anomaly was observed in Northern mid-latitude ecosystems during 2000–2016 compared to 1982–1998 (Gampe et al., 2021). Yin et al. (2023) has demonstrated that different vegetation types exhibit varied responses to drought and heatwave events. Specifically, for the Amazon and Southern Europe, extreme drought and heatwaves offset the enhanced GPP caused by CO<sub>2</sub> fertilization. Yuan et al. (2016) found that GPP in southern China significantly decreased due to the 100-year heatwave and drought in the summer of 2013, and crop yield also showed the largest negative anomaly since 1960. Extreme events can lead to significant losses in GPP, which in turn can seriously affect terrestrial ecosystem carbon sinks. Therefore, understanding the response of terrestrial GPP to extreme climate events such as heat and drought is important for predicting the response of global terrestrial ecosystems to future climate change (Beer et al., 2010; M. Wang et al., 2018).

The Tibetan Plateau (TP) boasts a delicate ecological balance, primarily covered by alpine grassland, making its vegetation highly sensitive to climate variations (Piao et al., 2019). Notably, the TP experienced a warming rate approximately double the global average (Piao et al., 2010; Yao, 2019), leading to an extended growing season for vegetation and a partial enhancement in vegetation productivity (Huang et al., 2019; Z. Zhu et al., 2016). Consequently, a general greening trend has been observed across the TP (Teng et al., 2021; X. Wang et al., 2019), although localized browning phenomenon has also been reported (P. Li et al., 2020). However, the southern and western parts of the TP have faced escalating drought conditions, resulting in the degradation of local vegetation (C.-P. Wang et al., 2021; Z. Wang et al., 2021). In the context of global climate change, changes of vegetation in the TP show significant spatial heterogeneity (Zhang et al., 2015), reflecting the complex interplay between regional climatic shifts and ecological responses.

In the summer of 2022, a global heatwave swept across countries, particularly in the northern hemisphere, where temperatures soared above 40°C, breaking the historical extreme maximum temperature (Hua et al., 2023). In June 2022, surface air temperature (TAS) surged in the middle and lower regions of the Yangtze River and Yellow River in China, and this TAS anomaly gradually got strengthened until August, with significant abnormal high temperatures occurring from the western TP to the entire Yangtze River basin (X. Li et al., 2023). Moreover, J. Wang, Yan, et al. (2023) has demonstrated that this unprecedented event led to the most significant decline in vegetation greenness and GPP in the Yangtze River basin since 2000.

The high summer temperatures in the TP in 2022 have the potential to increase evapotranspiration. Coupled with low precipitation (PRE), it can exacerbate soil moisture deficit. However, different from the Yangtze River basin, temperature rise may promote TP's vegetation photosynthesis, but extreme drought could definitely lead to negative GPP anomalies. Till now, it is not clear how the promoting effect of high temperatures and the adverse effect of water scarcity would simultaneously affect vegetation in the TP. Therefore, we here aim to investigate the impact of this extreme compound heat and dry event on TP's vegetation photosynthesis in the TP. And a previous study suggested that changes of vegetation in spring and summer should be analyzed as a whole due to their strong correlation (Sippel et al., 2016). In our research, we focus on the entire growing season to better comprehend the variation of vegetation photosynthesis in 2022. Our objective is to shed light on the intricate relationship between climate variations and vegetation photosynthesis in the TP.

## 2. Data and Methods

### 2.1. Climate Data

In this study, meteorological data, including 2 m dewpoint temperature (TD), TAS, total PRE, volumetric soil water (SW), and shortwave downward radiation (SWD) are all from the monthly averaged ERA5-Land product with the horizontal resolution of 0.1° × 0.1° (Muñoz, 2019). ERA5-land is a reanalysis data set generated by replaying the land component of the ECMWF ERA5 climate reanalysis, with an enhanced resolution compared to ERA5. Reanalysis uses the laws of physics to combine model data with observational data from around the world into a globally complete and consistent data set. Reanalysis produces data going back decades, providing an accurate description of the climate of the past.

Given that the volumetric SW here contains four layers with different depths (0–7 cm, 7–28 cm, 28–100 cm, and 100–289 cm), we calculated their depth-weighted average result of a depth of 289 cm. Additionally, the vapor pressure deficit (VPD) was derived according to the following formula used in a previous study (J. Wang, Zeng, et al., 2023):

$$\text{VPD} = 0.61078 \times \left( e^{\frac{17.27 \times \text{TAS}}{\text{TAS} + 237.29}} - e^{\frac{17.27 \times \text{TD}}{\text{TD} + 237.29}} \right) \quad (1)$$

where TAS and TD are in degrees Celsius, respectively. The VPD is in kilopascals (kPa). According to the suggestion of He et al. (2022), the monthly VPD anomalies calculated using daily and monthly data from ERA5 were almost same. Hence, we calculated the VPD directly using the monthly TAS and TD in this study.

## 2.2. Vegetation Photosynthesis Data

Two satellite-derived GPP products were used in this study, including the FluxSat GPP v2.2 and OCO-2-based Solar-induced chlorophyll fluorescence (GOSIF) GPP v2 products. Specifically, the daily FluxSat GPP was generated by satellite-based geometry-adjusted reflectance from the Moderate Resolution Imaging Spectroradiometer (MODIS) and FLUXNET 2015 flux tower data, based on a neural network method within a simplified light-use efficiency framework (Joiner et al., 2018). Importantly, the FluxSat GPP shows a high consistency with flux data at most sites. In this study, we aggregated daily FluxSat GPP into monthly. The GOSIF GPP was generated by eight SIF-GPP linear relationships for variety of biomes at both sites and grid cell levels based on the OCO-2 SIF data, combined the information of enhanced vegetation index, temperature, photosynthetically active radiation, and VPD. And it is proved that the GOSIF ensemble mean GPP is generally highly correlated with flux tower GPP at 91 eddy covariance flux sites across the globe (X. Li & Xiao, 2019). Both the FluxSat and GOSIF GPP products have a spatial resolution of 0.05° from March 2000 to December 2022.

In addition, we also calculated the near-infrared reflectance of vegetation (NIRv) proposed by Badgley et al. (2017) as a proxy of GPP to investigate the variation of vegetation photosynthesis. The NIRv obtained by multiplying Normalized Difference Vegetation Index (NDVI) with near-infrared reflectance (NIR):

$$\text{NIRv} = (\text{NDVI} - 0.08) \times \text{NIR} \quad (2)$$

In this paper, NDVI and NIR were from the Terra MODIS Vegetation Indices Monthly (MOD13C2) Version 6.1 product at the 0.05° climate modeling grid resolution. According to the data quality given by MODIS, only “good” pixels were retained. In addition, pixels with NDVI < 0.1 were excluded because they were basically non-vegetated areas. For uniform spatial resolution, we resampled it to 0.1° × 0.1° by nearest neighbor algorithm.

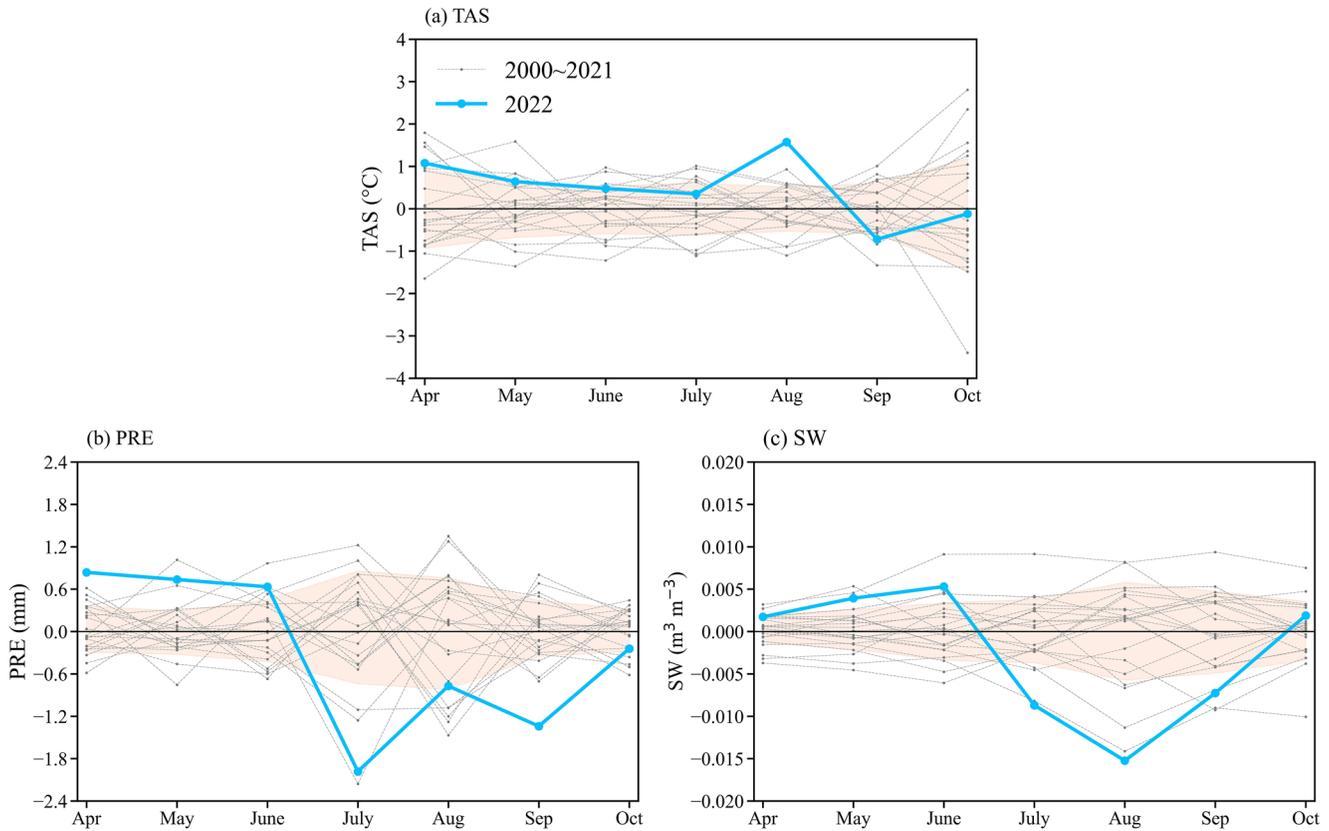
## 2.3. Attribution of Climate Drivers

Structural Equation Modeling (SEM) provides a framework for multivariate analysis of networks and paths (Grace et al., 2012). SEM can quantitatively describe the causal relation between covariates and dependent factor, and judge whether the relationship between variables is significant. In this study, we used SEM to explore the relationship between vegetation photosynthesis and various climate variables, including TAS, VPD, PRE, and SW. Additionally, SEM was used to explore the interrelationships among these climate variables. The SEM analyses were conducted using R with Lavaan Package (Rosseel, 2012). Model fit ( $\chi^2$ ), tests of individual parameters ( $p$  value), goodness of fit index, and root mean square error of approximation (RMSEA) were employed to evaluate model fitness and whether the sign and strength of directional paths in SEM were appropriate. Generally,  $\chi^2$  assesses overall fit, and larger value means better fit model. Contrary to previous perceptions,  $p > 0.05$  would be ideal, and a non-significant  $p$ -value means that our hypothesized relationship cannot be rejected. And goodness of fit index (GFI) takes values of  $\leq 1$  where 1 represents a perfect fit. RMSEA indicates model misspecification, ranging from 0 (perfect fit) to higher values (lack of fit) (Fan et al., 2016).

## 3. Results

### 3.1. Anomalies of Climate and Vegetation Photosynthesis in the 2022 Growing Season

In the summer of 2022, extreme heatwaves raged across the country, especially in the Yangtze River basin (J. Wang, Yan, et al., 2023). And we can find that the TP also experienced the record-breaking heat in August 2022, showing the highest positive temperature anomaly since 2000, far surpassing one standard deviation ( $1\sigma$ ) (Figure 1a). Rather, warm temperatures actually persisted from April to August 2022. Concurrently, more PRE was observed during the

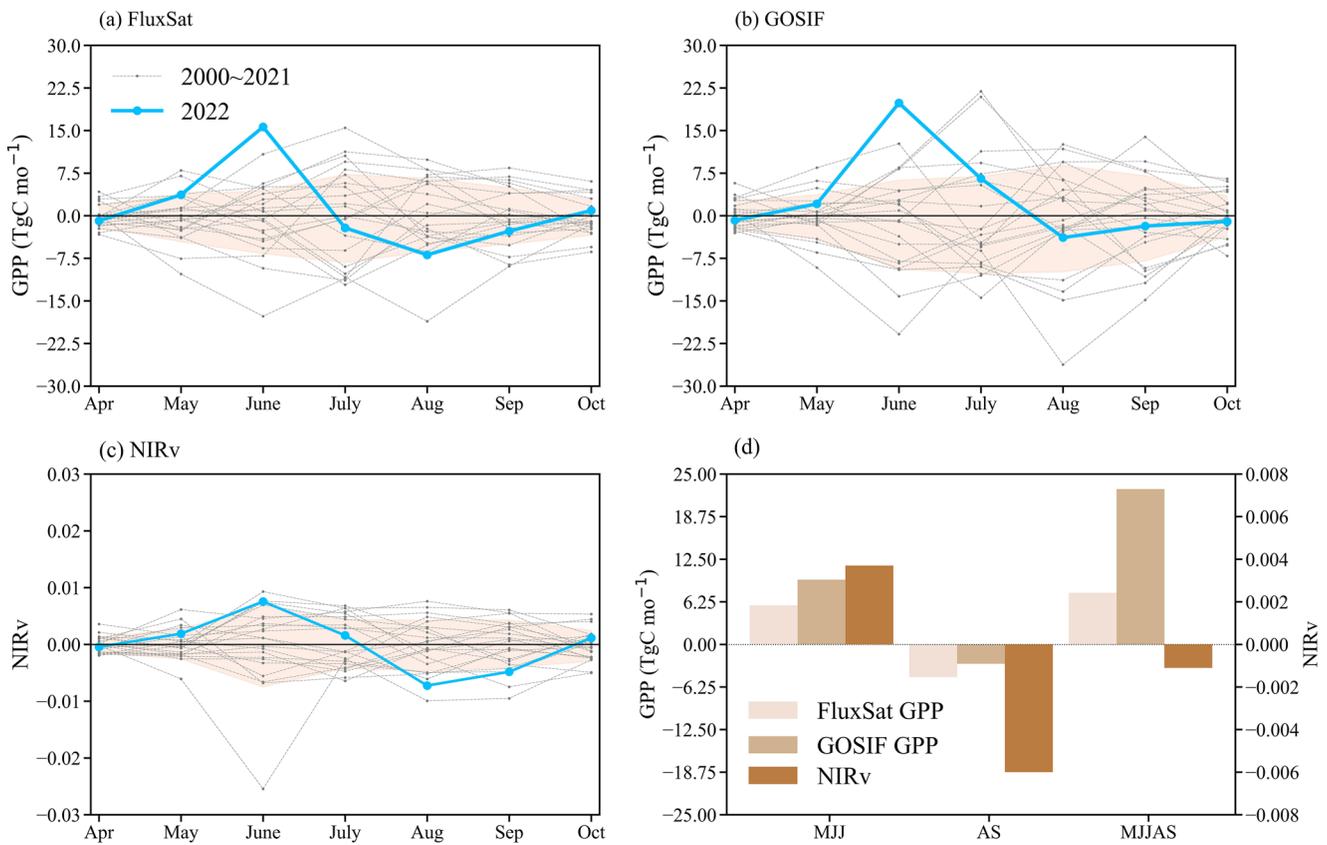


**Figure 1.** Climate anomalies over the Tibetan Plateau (TP) during the growing season in 2022. (a) Surface air temperature (TAS), (b) precipitation (PRE), and (c) volumetric soil water (SW). The blue lines show the climate anomalies in 2022. The shaded areas represent one standard deviation ( $1\sigma$ ) of the variation of each climate factor in the period of 2000–2021.

months spanning from April to June 2022. However, a noticeable shift occurred subsequently, marked by a significant reduction in PRE from July through October (Figure 1b). Additionally, as a result of the variation in PRE, the SW transitioned from relatively wet in the months of April to June to notably drier conditions thereafter. However, owing to the effect of so-called “soil memory” (J. Wang et al., 2016), the lowest SW occurred in August 2022 which lagged 1 month behind PRE (Figures 1b and 1c). Moreover, the reduced PRE, accompanied by decreased cloud cover, resulted in an increase in downward solar radiation, reaching its peak in July 2022 (Figure S1a in Supporting Information S1). Simultaneously, decreased atmospheric humidity also made VPD register its highest positive anomaly in July 2022 (Figure S1b in Supporting Information S1). Hence, these changes in water and heat in different months over the TP can have both promoting and adverse effects on the vegetation photosynthesis.

Figure 2 illustrates the anomalies of vegetation photosynthesis in 2022. In general, vegetation photosynthesis consistently suggested positive anomalies in the months from May to July with the most significant enhancement in June, in which the two GPP products show higher than  $2\text{-}\sigma$  variations in the period of 2000–2021. These enhancements in photosynthesis appear to be linked to prolonged high temperatures and increased SW levels (Figures 1a and 1d). Thereafter, vegetation photosynthetic activity was hampered, especially in August 2022, when FluxSat and NIRv displayed negative anomalies lower than  $-1\text{-}\sigma$ . Evidently, the decline in photosynthesis during this period can be largely attributed to the hot and dry conditions (Figures 1a and 1d). Interestingly, while high temperatures generally promote photosynthesis over the TP, drought conditions have an inhibiting effect. It is reasonable to speculate that the negative impact of drought on photosynthesis outweighed the promoting effect of heat, leading to the observed decline.

Given that GPP and NIRv did not show obvious anomalies in April and October, we calculated their averages in May–June–July (MJJ), August–September (AS), and May to September (MJJOS), respectively (Figure 2d). Quantitatively, in MJJ, the enhancement in photosynthesis suggested the magnitudes of  $5.724 \text{ TgC mo}^{-1}$  in FluxSat,  $9.491 \text{ TgC mo}^{-1}$  in GOSIF GPP products, and  $0.004$  in NIRv. In contrast, photosynthesis showed the decline



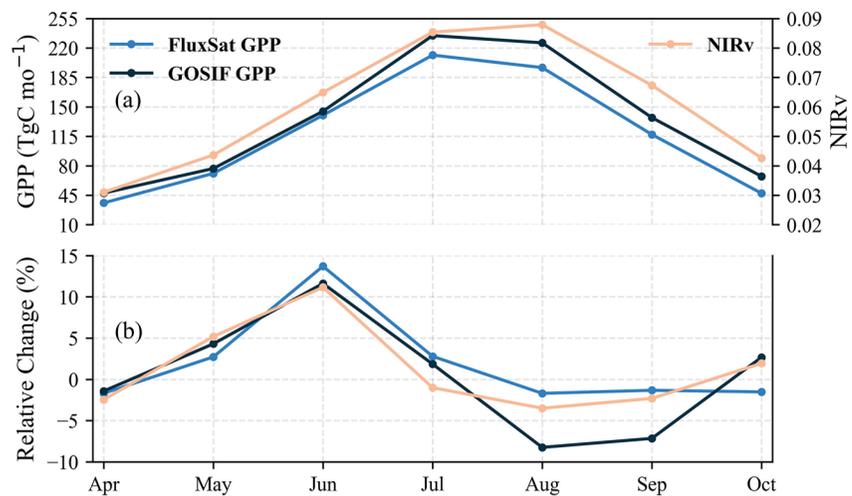
**Figure 2.** Vegetation photosynthesis anomalies over the Tibetan Plateau during the growing season in 2022. (a) FluxSat gross primary productivity (GPP), (b) OCO-2-based Solar-induced Chlorophyll Fluorescence (GOSIF) GPP, and (c) Moderate-resolution Imaging Spectroradiometer (MODIS) near-infrared reflectance of vegetation (NIRv). The blue lines show the anomaly in 2022, and the gray lines show anomalies in 2000–2021 with their 1- $\sigma$  in shaded. (d) Mean vegetation photosynthetic anomalies (GPP and NIRv) in May–June–July (MJJ), August–September (AS), and May to September (MJJOS), respectively.

in AS, with the magnitudes of  $-4.802 \text{ TgC mo}^{-1}$  in FluxSat,  $-2.837 \text{ TgC mo}^{-1}$  in GOSIF GPP, and  $-0.006$  in NIRv. Hence, enhancement in photosynthesis in MJJ counterbalanced the decline in AS, leading to the average positive GPP anomaly and weak negative NIRv anomaly in the entire growing season.

Vegetation photosynthesis in the TP increases fast in the months from April to July, peaks in July and August, and then decreases in September and October (Figure 3a). In order to more directly understand the changes in photosynthesis relative to the climatological seasonal cycle, we additionally derived their relative variations (Figure 3b). Clearly, the most substantial enhancement in photosynthesis occurred in June 2022, registering approximately 11.2% in FluxSat GPP, 13.7% in GOSIF GPP and 11.6% in NIRv. In contrast, the most significant reduction was observed in August 2022, with amplitudes of about  $-3.5\%$  in FluxSat GPP,  $-1.7\%$  in GOSIF GPP, and  $-8.3\%$  in NIRv.

### 3.2. Contribution of Different Climate Drivers to Vegetation Photosynthesis Variations

We examined the relationship between photosynthesis variations and climate drivers during the periods of positive anomaly in MJJ and negative anomaly in AS, using the SEM. Moreover, when studying the correlation between GPP/NIRv and climate drivers in AS, we introduced the average of the monthly total GPP/NIRv from May to July as an independent variable to explore the potential legacy effect of the preceding GPP/NIRv anomalies. We also calculated the correlation matrix to assess the interactions among climate drivers (Tables S1 and S2 in Supporting Information S1). Furthermore, variance inflation factors (VIFs) were employed to diagnose the potential co-linearity among these climate drivers in SEM, with the calculation principle of VIFs provided in the Method in Supporting Information S1. As per established criteria, a VIF within 10 for a climate variable indicates that there is no collinearity (Imdadullah et al., 2016; O'Brien, 2007). Our results showed VIFs of the predictor factors in all regression models were below 10 (Tables S3 and S4 in Supporting Information S1), indicating the absence of significant collinearity between variables in our model. In addition, as the effect of VPD and SWD



**Figure 3.** (a) Seasonal cycle of total gross primary productivity (GPP) and average near-infrared reflectance of vegetation (NIRv) over the Tibetan Plateau, calculated from 2000 to 2021. (b) Relative changes of vegetation photosynthetic anomalies in 2022.

exhibited non-significant effects on GPP anomalies in the SEM (Figure S2 in Supporting Information S1), these two variables were not considered in the following analysis in the main text.

Our model evaluation confirmed the efficacy of SEM in quantifying the contribution of climate drivers to vegetation photosynthesis (Figure 4). Specifically, the  $\chi^2$  ranged from 0.11 to 4.74,  $p$  exceeded 0.05. Additionally, GFIs approached 1, and RMSEAs generally approached zero, indicating a robust fit of the model. The standardized coefficient (SC) values provided quantification of the specific effects of individual climate drivers on the GPP and elucidated the causal relationships between these climate drivers.

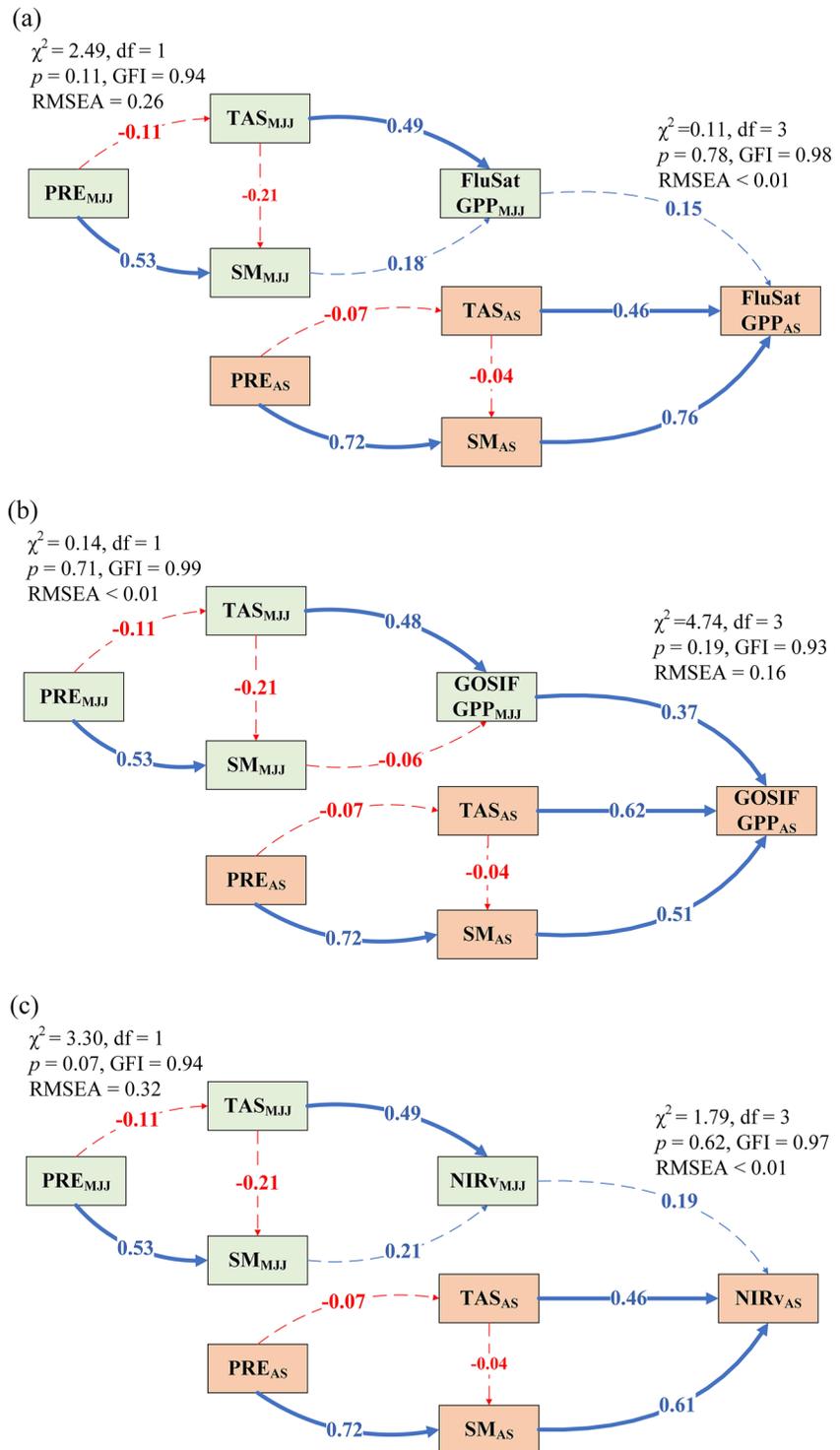
During the MJJ period, only temperature showed a significant positive correlation with GPP/NIRv, underscoring the pivotal role of temperature in driving vegetation photosynthesis. The SC between temperature and FluxSat, GOSIF GPP, and NIRv were 0.49, 0.48, and 0.49, respectively (Figures 4a–4c). This implies that warm conditions in the early growing season tend to stimulate vegetation growth, particularly in the relatively cold environment of the TP. Furthermore, SW displayed a significant positive correlation with PRE (SC = 0.53) but an insignificant negative correlation with temperature (SC = -0.21). However, SW did not exert a significant effect on GPP/NIRv. This indicates that during the initial stages of growth, vegetation in the plateau did not appear to be constrained by water availability.

Unlike the MJJ period, the variation of GPP and NIRv in AS was influenced by both temperature and SW, with SW exerting a lightly stronger impact, as indicated by the SC values. The SCs between FluxSat, GOSIF GPP, and NIRv and SW were 0.76, 0.51, and 0.61, respectively. Meanwhile, the SCs between these variables and temperature were 0.46, 0.62, and 0.46, respectively (Figures 4d–4f). This indicates that both SW and temperature played pivotal roles during the flourishing period of vegetation growth. In addition, the SC values of FluxSat GPP and NIRv with temperature slightly decreased in AS compared to MJJ. This indicated that the promoting effect of temperature on vegetation photosynthesis in the flourishing period might be weaker than in the early growing season. Furthermore, analyzing the correlation of climate drivers, PRE continued to be dominant factor influencing SW with a high correlation (SC = 0.72) in AS.

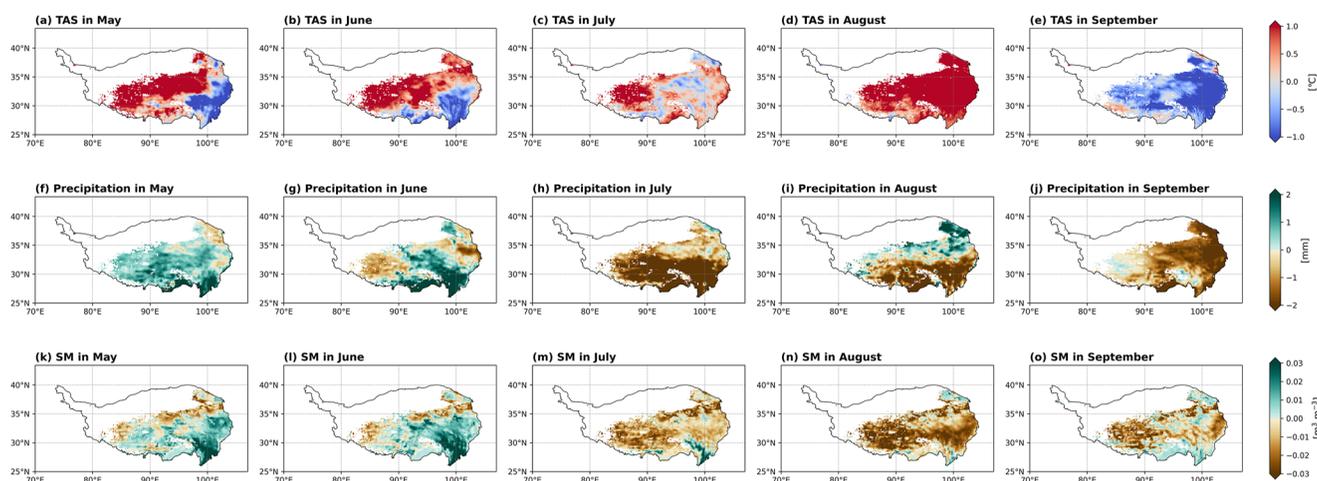
Additionally, the SEM results for GOSIF GPP revealed a significant positive influence of GPP in MJJ on GPP in AS. This suggests that robust vegetation photosynthesis during the early growing season might bolster vegetation's resilience against adversities in the subsequent period. In essence, the thriving photosynthesis in the initial stages could potentially fortify vegetation, enabling it to better withstand challenges during later phases.

### 3.3. Spatial Patterns of Climate and Vegetation Photosynthesis Anomalies Across Months

In order to better understand the progression of this extreme event associated with its influence on vegetation photosynthesis, we presented spatial patterns for their anomalies in the TP across different months (Figures 5 and 6). Remarkably, all three data sets showed good consistency in patterns of photosynthesis variations (Figure 6).



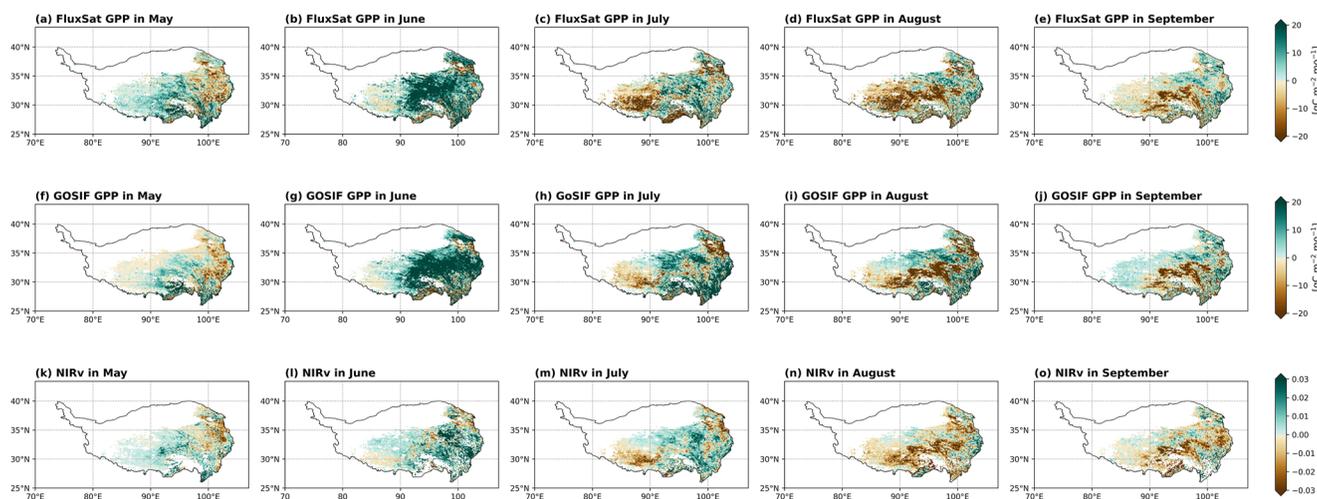
**Figure 4.** The relationship between photosynthesis variations and climate drivers in early and late summer of 2022 based on the Structural Equation Modeling (SEM) over the Tibetan Plateau. The part of the green filled boxes shows their relationships in early summer (May–June–July [MJJ]), and the red filled boxes is the results in late summer (August–September [AS]). The associations are examined in terms of FluxSat gross primary productivity (GPP) (a), GPP v2.2 and OCO-2-based Solar-induced chlorophyll fluorescence (GOSIF) GPP (b), and the near-infrared reflectance of vegetation (NIRv) (c). Standardized coefficients (SC) are indicated on lines with arrows, with solid lines denoting  $p < 0.01$ , and dashed lines denoting failure to pass the test.



**Figure 5.** Geographical distributions of detrended climate anomalies from May to September 2022 for the surface air temperature (TAS) (K) (a–e), precipitation (mm) (f–j), and soil water (SW) ( $\text{m}^3 \text{m}^{-3}$ ) (k–o).

In May and June, the TP was generally in a warm and humid environment, fostering an increase in vegetation photosynthesis (Figures 5 and 6). Nevertheless, spatial disparities in climate and photosynthesis anomalies were evident. Specifically, eastern and southeastern areas encountered unusual cold temperatures in May, resulting in the reduced GPP and NIRv despite adequate SW (Figures 5a, 5k, 6a, 6f, and 6k). It indicated the dominance of low temperatures impacted vegetation growth. By June, the negative temperature anomaly in the southeast lessened, coupled with sufficient SW, leading to nearly neutral GPP and NIRv values (Figures 5b, 5l, 6b, 6g, and 6l). Starting from July, PRE in the TP decreased sharply, resulting in a decline in SW (Figures 5h and 5m). However, due to the vegetation resistance, there has been no substantial negative anomalies in GPP and NIRv in July, except for the southwestern regions (Figures 6c, 6h, and 6m).

In August, high temperatures enveloped almost the entire TP (Figure 5d). Precipitation deficits persisted in the central and southern regions but increased in the north (Figure 5n). Despite this, the replenishment of water in the northern regions did not significantly improve SW; instead, the soil became drier throughout the TP due to enhanced evapotranspiration induced by high temperatures (Figure 5n). Consequently, despite the promoting effect of higher temperatures on vegetation photosynthesis (Figure 4), the extreme drought still led to the reduction in vegetation photosynthesis (Figures 6d, 6i, and 6n). Moving into September, temperature anomalies



**Figure 6.** Geographical distributions of detrended vegetation photosynthesis anomalies from May to September 2022 for the FluxSat gross primary productivity (GPP) ( $\text{gC m}^{-2} \text{mo}^{-1}$ ) (a–e), GPP v2.2 and OCO-2-based Solar-induced chlorophyll fluorescence (GOSIF) GPP ( $\text{gC m}^{-2} \text{mo}^{-1}$ ) (f–j), and near-infrared reflectance of vegetation (NIRv) (k–o).

transitioned from positive to negative (Figure 5e). Although PRE remained at extremely low levels (Figure 5j), negative SW anomalies moderated, especially in the south and central regions (Figure 5o), likely due to replenishment of meltwater and reduced evapotranspiration. Consequently, the inhibiting effect of vegetation photosynthesis was mitigated (Figures 6e, 6j, and 6o).

## 4. Discussion

### 4.1. The Linkage Between Warm Early Summer and Dry Late Summer

As we know, the response of vegetation to climate anomalies was multifaceted, with intricate interplay among various climate factors. Although it is recognized that warming during the early growing season is conducive to vegetation productivity (Schwartz et al., 2006; X. Wang et al., 2011), its advantages and disadvantages for vegetation growth need to be comprehensively explored in different regions. Previous studies have elucidated that increased evapotranspiration accompanying intense spring photosynthesis in plants may lead to a faster depletion of SW resources, amplifying the summer drought (Bastos et al., 2020; Sippel et al., 2016). And drier soils, in turn, would contribute to elevated summer temperatures, exacerbating adverse effects on vegetation productivity. This was exemplified by drought events in Europe in 2003 and 2010 (Miralles et al., 2014). Similarly, the increased vegetation photosynthesis in spring over the Northern Hemisphere during 1982–2011 triggered an additional SW deficit extending into summer, as demonstrated in a previous study (Lian et al., 2020). In addition, Angert et al. (2005) figured out that warming does not necessarily lead to higher CO<sub>2</sub> uptake, even in temperature-limited ecosystems (Zha et al., 2022).

In this study, the increased GPP in warm early summer counteracted the adverse impact of the extremely dry late summer in the TP, leading to an overall positive GPP anomaly for the entire growing season (Figure 2d). Our results in general align with the conclusion that warm spring could significantly compensate for the GPP decline, as suggested during the 2012 North American summer drought (Wolf et al., 2016). Furthermore, it is noteworthy that this seasonal compensation made a positive total GPP for the growing season in the TP in 2022. It contrasts with the Siberian 2020 heatwave, which increased spring CO<sub>2</sub> uptake without a corresponding annual CO<sub>2</sub> uptake increase (Kwon et al., 2021). This reminds us that net ecosystem exchange may not necessarily exhibit a positive anomaly during the 2022 growing season over the TP. Further studies should delve into understanding the response of ecosystem respiration to the warm early summer and hot dry late summer conditions in 2022.

Moreover, the faster warming rate has expedited the loss of soil and vegetation moisture, thereby reducing regional vegetation coverage, which has been verified in parts of the southern TP (Crausbay et al., 2017). Additionally, permafrost degradation resulting from global warming across the TP can significantly affect SW and nutrient supplies. Prolonged non-freeze periods tend to exacerbate summer soil desiccation (Baumann et al., 2009). Considering the ongoing global warming, warming in spring and heatwaves in summer are expected to become more frequent. If the frequency and intensity of these extreme events surpass the adaptive capacity of TP vegetation, there is a risk of further declines in vegetation productivity, which needs in-depth exploration (Sippel et al., 2016).

### 4.2. Seasonal Legacy Effect

In our study, there was a significant positive correlation between GOSIF GPP in early summer and GPP in late summer (Figure 4e), which means that there may be a seasonal legacy in vegetation physiological activities (Bastos et al., 2020; Yan et al., 2023). Previous studies have also shown that warmer early growth conditions can increase photosynthesis and enhance carbon sequestration. These conditions stimulated root growth, enabling vegetation to access deeper groundwater resources, enhancing its resilience against drought, and facilitating a faster recovery after subsequent droughts (Y. Li et al., 2023). This is maybe also reflected in our study. Even during the sharp decline in soil moisture and simultaneous significant rise in VPD in July 2022, the GPP did not immediately exhibit a substantial negative anomaly (Figures 2 and 6). Furthermore, Bastos et al. (2020) indicated that regional asymmetries in summer ecosystem carbon fluxes over the central and northern Europe can be partially explained by distinct legacy effects of spring warming in 2018 extreme heat and drought event. Spring climate anomalies amplified the negative impacts of summer drought in southern Europe, while contributing a positive legacy to summer Net biome productivity in higher latitude regions. This highlights that seasonal legacy of vegetation varied in the different vegetation types in different climatic zones, as evidenced by the study of Wu

et al. (2018). Additionally, differences in plant rooting systems and water use strategies in different regions may also lead to the asymmetric summer GPP anomalies (Wu et al., 2018).

Furthermore, our results indicate that the existence and nature of the legacy effects depend significantly on the data sets used. To be specific, the seasonal legacy effects on vegetation photosynthesis were significantly based on the GOSIF GPP, but insignificantly on the FluxSat GPP and MODIS NIRv (Figure 4). It is necessary for us to further investigate the seasonal legacy of vegetation here using the higher spatial resolution and higher quality data sets. Overall, these phenomena underscore the importance of understanding the intricate relationship between early growth conditions, subsequent environmental stressors, and vegetation's adaptive responses.

### 4.3. Implications and Prospects

The extreme heat and drought event in the Yangtze River Basin in China in 2022 has attracted wide attention (Hua et al., 2023; X. Li et al., 2023; Ma & Yuan, 2023; J. Wang, Yan, et al., 2023). Concurrently, the TP experienced both extreme high temperatures and low PRE during the summer of 2022, reaching levels unprecedented since 2000. However, our study reveals that the abnormal reduction of GPP in the TP is not as severe as observed in the Yangtze River Basin (J. Wang, Yan, et al., 2023). This discrepancy underscores the distinct response of the TP's vegetation to heat and drought events. On one hand, the warm and humid climate of the TP in early summer promoted GPP and increased the resistance of vegetation. Moreover, given that the vegetation on the TP is predominantly plateau grassland, its sensitivity to temperature is different from that of the Yangtze River basin at the same latitude. In this context, high temperatures can actually promote GPP on the TP (Figure 4). Nevertheless, whether there exists a critical point beyond which rising temperatures cease to enhance vegetation photosynthesis, and how high temperatures qualify as a heatwave on the TP need further research.

According to the IPCC AR6 (IPCC, 2022), the frequency of future heat and drought events would increase in the context of global warming. It's worth noting that high temperatures often co-occur with drought due to their role in intensifying evapotranspiration. In our study, it is found that when both high temperatures and drought coincided during the summer, the inhibitory effect of drought on GPP overweighed the promoting effect of temperature. Of course, the effect of SW scarcity on GPP is slightly higher than that of TAS during the late summer, but may be positive if the high temperature drought occurs during the temperature-dominated spring in the energy-limited TP ecosystem (Miller et al., 2023). Given the unique characteristics of the TP, further analysis is warranted to understand vegetation responses to the intricate compound extreme events involving heat and drought. This analysis should be conducted with consideration for the intensity of these specific events in this particular region.

## 5. Conclusion

In our study, we delved into the impact of the extreme heat and dry event during the summer of 2022 on vegetation photosynthesis in the TP. We revealed that high temperatures persisted from April to August 2022, reaching a historic peak in August—an unprecedented temperature anomaly since 2000. During this period, both PRE and SW exhibited positive anomalies in spring but transitioned to negative anomalies in summer. Notably, July experienced the lowest PRE, while SW reached its minimum in August, owing to the “soil memory.”

Consequently, GPP showed conspicuous positive anomalies in early summer, due to the warm environment. The peak positive anomaly occurred in June 2022. Subsequently, GPP anomalies turned negative in August and persisted until September due to the extreme summer drought event. This means the substantial increase in GPP during early summer mitigated the impact of this extreme event in late summer, resulting in an overall positive anomaly in total GPP for the entire growing season. So, we think that compensatory effects between seasons might alleviate the severity of carbon uptake deficits induced by climate extremes.

Furthermore, we suggested that the dominant climate factors of photosynthesis anomalies were different in different periods. Specifically, during early summer, temperature emerged as the primary factor, while GPP and NIRv were notably controlled by both temperature and SW in late summer, with a higher correlation between SW and GPP.

In space, the three data sets reflecting vegetation photosynthesis—FluxSat GPP, GOSIF GPP, and MODIS NIRv—exhibited good spatial consistency. The spatial evolution patterns of GPP and climate drivers showed the

process of GPP anomaly with climate change in 2022 growing season in more detail, which proved our results, and also showed the difference of dominant factors of GPP in different periods.

### Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

### Data Availability Statement

ERA5-Land are available at <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=overview>. FluxSat GPP Version 2.2 are available at [https://avdc.gsfc.nasa.gov/pub/tmp/Flux-Sat\\_GPP](https://avdc.gsfc.nasa.gov/pub/tmp/Flux-Sat_GPP). GOSIF GPP v2 are available at [http://data.globalecology.unh.edu/data/GOSIF-GPP\\_v2/](http://data.globalecology.unh.edu/data/GOSIF-GPP_v2/). The MODIS NDVI and NIR are provided at <https://lpdaac.usgs.gov/products/mod13c2v061/>.

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