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LETTER

Higher absorbed solar radiation partly offset the negative effects of water stress on the photosynthesis of Amazon forests during the 2015 drought

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Abstract

Amazon forests play an important role in the global carbon cycle and Earth’s climate. The vulnerability of Amazon forests to drought remains highly controversial. Here we examine the impacts of the 2015 drought on the photosynthesis of Amazon forests to understand how solar radiation and precipitation jointly control forest photosynthesis during the severe drought. We use a variety of gridded vegetation and climate datasets, including solar-induced chlorophyll fluorescence (SIF), photosynthetic active radiation (PAR), the fraction of absorbed PAR (APAR), leaf area index (LAI), precipitation, soil moisture, cloud cover, and vapor pressure deficit (VPD) in our analysis. Satellite-derived SIF observations provide a direct diagnosis of plant photosynthesis from space. The decomposition of SIF to SIF yield ($SIF_{\text{yield}}$) and APAR (the product of PAR and fPAR) reveals the relative effects of precipitation and solar radiation on photosynthesis. We found that the drought significantly reduced $SIF_{\text{yield}}$, the emitted SIF per photon absorbed. The higher APAR resulting from lower cloud cover and higher LAI partly offset the negative effects of water stress on the photosynthesis of Amazon forests, leading to a smaller reduction in $SIF_{\text{yield}}$ and precipitation. We further found that $SIF_{\text{yield}}$ anomalies were more sensitive to precipitation and VPD anomalies in the southern regions of the Amazon than in the central and northern regions. Our findings shed light on the relative and combined effects of precipitation and solar radiation on photosynthesis, and can improve our understanding of the responses of Amazon forests to drought.

1. Introduction

The Amazon rainforests are one of the largest, most productive, and most biodiverse terrestrial ecosystems, and account for more than half of the Earth’s tropical rainforests (Nölscher et al 2016, Saatchi et al 2011). Amazon forests play an important role in regulating the global carbon cycle and the Earth’s climate (Baker et al 2008, Lewis et al 2011). Precipitation and solar radiation are the two most important environmental factors controlling the photosynthetic activity of Amazon forests. Previous studies showed that Amazon forests are sensitive to climate variability and change, particularly drought (Baker et al 2008, Lewis et al 2011). Drought can alter the photosynthesis, leaf area index (LAI), and surface energy exchange of Amazon forests (Saleska et al 2003, Wright and Vanschaik 1994), and these changes can in turn affect the regional and global climate (Alden et al 2016). Therefore, better understanding the responses of Amazon forests to drought...
drought is critical for projecting the terrestrial carbon uptake and the Earth’s climate.

How the photosynthesis of Amazon forests responds to drought has been highly controversial over the last 15 years. A number of studies have examined the impacts of drought on the photosynthesis of Amazon forests, with some showing positive impacts and others showing negative impacts. A previous study based on eddy covariance data showed that canopy photosynthesis increased in the dry season (Saleska et al. 2003), likely because of the increased LAI with higher solar radiation (Wright and Vanschaik 1994) and the access of deep-rooted trees to water in deep soil layers (Nepstad et al. 1994). Similarly, using measurements from eddy covariance flux sites, two recent studies also reported increased photosynthesis of Amazon forests in the dry season (Wu et al. 2016, Restrepo-Coupe et al. 2017). Using the enhanced vegetation index (EVI) derived from the MODerate resolution Imaging Spectroradiometer (MODIS), two studies showed that the 2005 drought led to ‘green up’ (i.e., an increase in photosynthetic activity) in Amazon forests (Huete et al. 2006, Saleska et al. 2007). These two studies suggested that sunlight may exert a larger influence on rainforest phenology and productivity than precipitation, and intact Amazon forests may be less vulnerable to climate variations than many ecosystem models assume.

By contrast, some studies based on either site or satellite observations showed that forests suffered from declines in canopy photosynthesis under water stress (Malhi et al. 1998, Liu et al. 2017). For example, Doughty et al. (2015) estimated that the severe drought in 2011 suppressed Amazon-wide photosynthesis by 0.38 Pg C. Several satellite-based studies indicated that the previous results of large-scale greening of the Amazon in drought based on MODIS EVI data resulted from inclusion of atmosphere-corrupted data (Bi et al. 2016, Maeda et al. 2014, Morton et al. 2014, Samanta et al. 2010). Based on MODIS EVI data with improved sensor calibration, sun-sensor geometry normalization, cloud detection, and atmospheric correction, these studies indicated that the 2005 drought showed no influence on, or even decreased, the greenness of Amazon forests. Another study indicated that the solar-induced chlorophyll fluorescence (SIF) derived from the Greenhouse Gases Observing SATellite decreased in the dry season over the central and southern Amazon, suggesting a decrease in gross primary productivity (GPP) due to water stress (Lee et al. 2013). Therefore, the direction of photosynthesis changes in Amazon forests during drought and the relative effects of solar radiation and precipitation, remain unclear.

In recent years, satellite SIF measurements have opened a new perspective on the monitoring of global vegetation photosynthetic activity (Frankenberg et al. 2011, Guanter et al. 2012, Joiner et al. 2013, Joiner et al. 2011, Joiner et al. 2014, Li et al. 2018). The SIF is essentially a ‘glow’ of plants under sunlight, which is emitted from plant chlorophyll molecules a few nanoseconds after light absorption in the wavelength range of 600–800 nm (Baker 2008). Light energy absorbed by the leaf chlorophyll molecules takes three different pathways: photochemistry, non-photochemical quenching (NPQ, i.e., heat dissipation), and re-emission as SIF (Baker 2008). Only a small fraction undergoes re-emission. SIF is highly correlated with photosynthesis when NPQ dominates at high light levels (Baker 2008). SIF is strongly correlated with photosynthesis as both are mainly determined by absorbed photosynthetic active radiation (APAR), and are also influenced by temperature and water stresses (Li et al. 2018). Compared to traditional vegetation indices such as the normalized difference vegetation index (NDVI) and EVI, the SIF is generated by the photosynthetic machinery itself, and therefore may provide a quick and direct diagnosis of the actual photosynthesis status of vegetation (Meroni et al. 2009). The superiority of SIF for monitoring drought stress has already been demonstrated, especially when vegetation remains green while photosynthetic activity weakens (Daumard et al. 2010, Joiner et al. 2014, Wang et al. 2016, Yoshida et al. 2015).

Here we examined the impacts of the 2015 drought on the photosynthesis of Amazon forests, and explored the underlying mechanisms of how radiation and precipitation jointly control photosynthesis during severe drought. How this drought affected the photosynthesis of Amazon forests remains unclear. We used a variety of vegetation and climate variables including SIF, photosynthetic active radiation (PAR), fraction of APAR (fPAR), LAI, precipitation, soil moisture, vapor pressure deficit (VPD), and cloud cover to answer the following two questions: (1) how did the photosynthesis of Amazon forests respond to the 2015 drought?; (2) what were the relative effects of solar radiation and precipitation on the photosynthesis of Amazon forests during the 2015 drought? SIF along with PAR and the APAR could provide insight into the component processes that are responsible for the changes in SIF during drought. Our findings can improve our understanding of the responses of Amazon forests to drought.

2. Materials and methods

2.1. SIF

Currently, the GOME-2 instrument onboard Eumetsat’s MetOp-A platform provides the global satellite SIF dataset with the longest duration and highest fidelity (Joiner et al. 2013, Joiner et al. 2011). We used the monthly SIF data retrieved from the GOME-2 red band from 2007–2015 (Joiner et al. 2016). The red SIF data were partially filtered for clouds by removing pixels with effective cloud fractions up to 30%, and the pixels with solar zenith angles greater than 70° were also eliminated to avoid possible biases.
due to rotational Raman scattering (Vasilkov et al 2013). The performance of red SIF was evaluated by a comparison with far-red SIF in different areas. The spatio-temporal anomalies of red SIF and far-red SIF were similar, particularly in drought-prone regions (Joiner et al 2016). There was a larger percentage response in SIF in the red wavelength than in the far-red wavelength in drought-affected regions (Joiner et al 2016). MetOp-A GOME-2 has encountered radiometric degradation over its lifetime (Joiner et al 2016), which leads to a declining trend in SIF in the far-red wavelength. By contrast, the red SIF has been calibrated based on irradiance changes that occurred at 690 nm. The red SIF is therefore likely more reliable than the far-red SIF data for interannual variability or trend analysis. In this study, we used the newly released monthly GOME-2 red SIF data from 2007 to 2015 (https://avdc.gsfc.nasa.gov). Unlike the far-red SIF, the red SIF dataset was produced at a resolution of 1° to reduce the impact of retrieval noise.

GOME-2 SIF products are inherently noisy due to low signal levels, and some negative values owing to imperfect bias correction and noise can be found in the monthly Level 3 data. These negative monthly values were suggested to be either treated as zero for certain applications or retained in other applications such as averaging over a number of years. Amazon forests have a naturally high photosynthetic capacity, and the majority of the pixels have positive monthly SIF values throughout the year. We treated the small percentage of negative values as zero.

2.2. MODIS data products
We used the LAI (Myneni et al 2002), fPAR (Myneni et al 2002), and land cover (Friedl et al 2010) products in this study. These data products were obtained from the Land Processes Distributed Active Archive Center (LP DAAC; https://lpdaac.usgs.gov) for the period 2007–2015.

The fPAR measures the proportion of available radiation in the photosynthetically active wavelengths that is absorbed by vegetation canopies. We used fPAR to examine the effects of the fPAR variations on SIF because it is an important component of SIF. The fPAR is closely related to LAI, which defines the one-sided leaf area per unit of horizontal ground area. The MOD15A2 LAI and fPAR products used in this study are available every eight days and at 1 km resolution.

The Land Cover Type Climate Modeling Grid (MCD12C1) provides the dominant land cover types at a spatial resolution of 0.05°. We used the MCD12C1 land cover map in 2012 with the University of Maryland land cover classification scheme to identify forest pixels.

2.3. Precipitation data, soil moisture, cloud cover, VPD, and solar radiation data
We used monthly Tropical Rainfall Measuring Mission (TRMM) precipitation data at 0.25° spatial resolution over the period 2007–2015 (3B43—Version 7). The TRMM 3B43 data were downloaded from the Goddard Earth Sciences Data and Information Services Center (GES DISC, http://disc.sci.gsfc.nasa.gov). TRMM precipitation data have been widely used to examine the patterns and anomalies of precipitation in tropical regions (Lee et al 2013, Guan et al 2015, Xu et al 2015).

The monthly soil moisture and cloud cover data over the period 2007–2015 were obtained from the Global Land Data Assimilation System (GLDAS) data product GLDAS-2 from the GES DISC (http://disc.sci.gsfc.nasa.gov). The dataset contains a series of land surface parameters simulated from the Noah 2.7.1 model at a 0.25° spatial resolution and a monthly time step. There were four vertical levels for soil moisture in the Noah model: 0–0.1 m, 0.1–0.4 m, 0.4–1.0 m, and 1.0–2.0 m. The Noah model uses a 1 m root depth for grasslands and crops, and 2 m for woodland and forest. Therefore, in this study, we accumulated the soil moisture from the four soil layers to characterize the water variations in the whole root system of Amazon forests. Previous studies showed that the Noah model generally had good performance in simulating soil moisture, but the resulting estimates could have substantial uncertainty (Kim et al 2015, Fang et al 2016). Moreover, the roots of Amazon forests can be as deep as ~18 m (Nepstad et al 1994), and the water availability of these forests is likely not well characterized by the soil moisture of the top 2 m soil layer. Therefore, we also used VPD to measure atmospheric water stress.

The monthly VPD was calculated based on mean temperature and relative humidity data from the Modern-Era Retrospective Analysis for Research and Applications (MERRA-2, Version 2) meteorological reanalysis data. The MERRA-2 data are available at a spatial resolution of 0.5°×0.625°, and were obtained from the NASA GES DISC (https://disc.sci.gsfc.nasa.gov). We used the anomalies of VPD as a measure of drought severity.

We used the monthly solar radiation data at a 1° spatial resolution over the period 2007–2015 from the Level 3 Monthly Radiative Fluxes and Clouds (SYN1deg-Month Ed3A) products. The solar radiation data were obtained from the NASA Langley Research Center Atmosphere Science Data Center (https://eosweb.larc.nasa.gov). The total surface PAR in all-sky conditions was calculated as the sum of the surface diffuse PAR and direct PAR in all-sky conditions.

2.4. Gridded GPP data
We used gridded GPP data (Xiao et al private communication) upscaled from FLUXNET observations to demonstrate that GOME-2 SIF is a good proxy for the GPP of Amazon forests. This GPP product was upscaled from flux tower GPP data to the global scale using a data-driven approach (Xiao et al 2008, 2010, 2014) along with MODIS data
streams and meteorological reanalysis data. A predictive GPP model was first developed at the site level using GPP data, meteorological data, and MODIS data streams for 253 eddy covariance flux sites across the globe. The model was then used to estimate the GPP for each 0.05 degree grid cell over the globe for each eight-day period and each month over the period of 2000–2010. The resulting upscaled global GPP product, EC-MOD (Xiao et al private communication), is highly constrained by GPP estimates from eddy covariance flux towers.

2.5. Rationale for SIF dynamics

The amount of SIF at the top of the canopy can be formulated in a similar form as the GPP model based on the light use efficiency (LUE) logic (Guanter et al 2014, Sun et al 2015, Yoshida et al 2015):

\[ SIF = f\text{PAR} \times PAR \times SIF_{\text{yield}} = \text{APAR} \times SIF_{\text{yield}} \] (1)

where \( SIF_{\text{yield}} \) is the emitted SIF per photon absorbed, and is the product of the actual fluorescence yield of the canopy and the fractional amount of fluorescence that escapes the canopy. The actual dynamics of SIF can originate from fPAR, PAR, and SIF\(_{\text{yield}}\).

Two important variables can lead to better understanding of their individual contributions to SIF when remotely sensed fPAR and PAR are available. One of the two variables is SIF normalized by PAR, referred to as SIF\(_{\text{PAR,norm}}\) hereafter. SIF\(_{\text{PAR,norm}}\) can be expressed as follows:

\[ SIF_{\text{PAR,norm}} = \frac{SIF}{PAR} = f\text{PAR} \times SIF_{\text{yield}} \] (2)

SIF\(_{\text{PAR,norm}}\) eliminates the effects of PAR on SIF. The variations of SIF\(_{\text{PAR,norm}}\) results from changes in vegetation structure that may affect LAI and chlorophyll content, and from changes in vegetation physiological and biochemical states that can affect SIF\(_{\text{yield}}\), which is the other important variable. SIF\(_{\text{yield}}\) is SIF\(_{\text{PAR,norm}}\) further normalized by fPAR or SIF normalized by APAR. SIF\(_{\text{yield}}\) can be written as follows:

\[ SIF_{\text{APAR,norm}} = SIF_{\text{yield}} = \frac{SIF}{f\text{PAR} \times PAR}. \] (3)

SIF\(_{\text{yield}}\) eliminates the effects of APAR on SIF, and indicates the effective fluorescence yield of the canopy.

The use of SIF\(_{\text{PAR,norm}}\) and SIF\(_{\text{yield}}\) can help us understand the dynamic processes of SIF during drought because a drought can be accompanied by higher PAR and APAR. Two recent studies have investigated the seasonal cycles of these variables during drought, and revealed the effects of PAR and water stress on SIF during drought (Sun et al 2015, Yoshida et al 2015).

2.6. Data analysis

The data used in this study have different spatial and temporal resolutions. The SIF and PAR data are available at a 1° spatial resolution, precipitation, soil moisture, and cloud cover data at 0.25° resolution, VPD at 0.5° x 0.625° resolution, MODIS fPAR at 1 km resolution, and MODIS land cover at 0.05° resolution. The precipitation, soil moisture, cloud cover, VPD, fPAR, and land cover were spatially aggregated to 1° spatial resolution to match the resolution of SIF and PAR data. For the land cover data, the dominant land cover class, defined as the class with the highest percent cover, was assigned to each 1° pixel (figure 1). In addition, the eight-day fPAR data were temporally aggregated into monthly means to match the temporal resolution of other datasets using a linear weighted method.

It has been reported that the responses of Amazon forests to precipitation and solar radiation can vary from north to south across the Amazon (Bradley et al 2011, Guan et al 2015, Lee et al 2013, Xu et al 2015). Therefore, we identified three regions that have distinct precipitation characteristics: (a) southeastern Amazon, with ecologically dry seasons (EDS; monthly rainfall 100 mm) more than three months; (b) central Amazon, with only 1–2 EDS months; and (c) northern Amazon, with everwet areas. These three regions were all affected by the 2015 drought. We made comprehensive comparisons of multiple vegetation and climate variables in 2015 relative to the multi-year means (2007–2014) in the three selected regions (figure 1). This allowed us to examine how SIF responded to the drought across the Amazon. One more region, located in the east of Brazil and dominated by dry savannas (region D in figure 1), was also selected to examine whether the change in photosynthesis of savannas was similar to that of forests during the drought.

Previous studies demonstrated that SIF is strongly correlated with GPP (Frankenberg et al 2011, Joiner et al 2011, Li et al 2018). We first examined the consistency in spatial and temporal patterns between GOME-2 SIF and the upscaled GPP product for the overlapping period of the two datasets (2007–2010). Figure S1 shows the seasonal variations of gridded GPP and GOME-2 SIF throughout the four seasons: January–February–March (JFM), April–May–June (AMJ), July–August–September (JAS), and October–November–December (OND). The annual mean was subtracted from the seasonal mean to show the seasonality in GPP and SIF. The GPP of the forests exhibited different variations across the Amazon, while the SIF could generally capture these variations (in OND, figure S1(d) and (h)). In the central and northern Amazon with a shorter length of EDS, both GPP and SIF exhibited small and similar variations within the year. There were generally higher GPP and SIF values in wetter seasons (figures S1(a), (d), (e), and (h)). The southern counterparts showed clear seasonal variations suggested by GPP and SIF. The GPP and SIF were lowest in the dry season (figures S1(c) and (g)), and highest (figure S1(a), (d), (e), and (h)) in the wet season. We then compared the seasonal cycles of monthly
Figure 1. (a) Land cover map of the Amazon, obtained from the 2012 MCD12C1 land cover map. The land cover map was resampled to 1° based on the dominant land cover classes. (b) Annual mean precipitation in the Amazon for the period of 2007–2014, derived from TRMM. The outline in the precipitation map line represents the Amazon basin. The four boxes represent (A) the southeastern Amazon (54°–59° W; 8°–12° S), (B) the central Amazon (60°–65° W; 2°–6° S), (C) the northern Amazon (62°–67° W; 1°–5° S), and (D) the east of Brazil (41°–46° W; 6°7’–14° S). They have different levels of annual precipitation.

3. Results and discussion

3.1. Anomalies of SIF

The drought started from August 2015 and aggravated in the following four months (supplementary figure S3 available at stacks.iop.org/ERL/13/044005/mmedia). This severe drought was comparable to the 2010 drought in terms of precipitation deficit and drought extent. The central and eastern Amazon basins experienced substantial decreases in precipitation and soil moisture during the drought (figures 2(a) and (b)). The total precipitation in JAS (dry season in the Amazon) in 2015 was slightly lower than that in 2010, and the total precipitation in OND in 2015 was much lower than that in 2010 (supplementary figure S4). The soil moisture in 2015 was slightly higher than that in 2010 for JAS, and much lower than that in 2010 for OND (supplementary figure S4). Both precipitation and soil moisture in OND of 2015 were the lowest over the period 2007–2015.

The SIF anomalies showed inconsistency with the anomalies in precipitation, soil moisture, and VPD in...
2015 at the annual scale to some extent (figure 2). Large negative anomalies of precipitation and soil moisture dominated the Amazon basin, suggesting that a large part of the basin was affected by the severe drought. About 54.7% and 39.6% of the forested pixels showed significant decreases in precipitation and soil moisture, respectively. Similar to precipitation and soil moisture, VPD exhibited nearly basin-wide positive anomalies (figure 2(c)), further suggesting that the severe drought led to a large water deficit. However, annual mean SIF did not show extensive negative anomalies despite the drought (figure 2). Only 18.2% of the forested pixels showed significant decreases in SIF, and these pixels were scattered across the Amazon. The spatial patterns of the SIF anomalies did not coincide well with the spatial distributions of precipitation and soil moisture anomalies. This indicates that the photosynthesis of Amazon forests may not have been seriously affected in 2015 despite the severe drought.

3.2. Higher APAR partly offset negative effects of water stress on photosynthesis

The drought had more pronounced impacts on SIFPAR$\text{norm}$ and SIFyield than on SIF (figure 3). The seasonal cycle of SIFPAR$\text{norm}$ largely resembled the SIF curve but with larger anomalies during the drought.
The seasonal cycles of eight vegetation and climate variables in the southeastern Amazon: (a) precipitation, (b) VPD, (c) PAR, (d) fPAR, (e) cloud cover, (f) SIF, (g) SIF_PAR_norm, and (h) SIF_yield. The red lines with plus symbols stand for the seasonal cycles of these variables in 2015, and the black lines with circles stand for the multi-year means of these variables over the period of 2007–2014.

The contrast between SIF_PAR_norm and SIF curves suggests that the higher PAR partly neutralized the negative effects of drought on SIF. This is generally consistent with the findings of two previous studies. Sun et al. (2015) evaluated two drought events with different onset mechanisms in Texas and the Great Plains in the United States using GOME-2 SIF. The drought was accompanied by high PAR, and once the effect of PAR was removed, the net impacts of drought on SIF became more pronounced. Yoshida et al. (2015) found negative anomalies in SIF_PAR_norm in areas composed primarily of mixed forest, while NDVI anomalies appeared to be smaller and occurred somewhat later. The SIF_yield during the 2015 drought had larger negative anomalies than SIF_PAR_norm (figure 3(h)) because high fPAR was observed during the drought (figure 3(c)). This coincides with the finding by Yoshida et al. (2015) that the negative anomalies were more prominently reflected in SIF_yield than that in SIF_PAR_norm in areas dominated by mixed forest because of concurrent high fPAR. This phenomenon was not observed in other vegetation types, but possibly related to the different responses of deeper-rooted mixed forests to drought. The SIF_yield eliminated the effects of vegetation structural variables (fPAR) on SIF_PAR_norm and could provide important information on environmental stresses that may not be rapidly reflected in vegetation greenness and chlorophyll content but have significant effects on the production of fluorescence (Sun et al. 2015).

The seasonal cycle of SIF_yield, to a large extent, resembled those of cloud cover and precipitation (figures 3(e) and (h)). The SIF_yield immediately dropped when the drought began, and its anomalies became larger in absolute magnitude as the drought aggravated. This phenomenon was not observed for SIF or SIF_PAR_norm. The similarity in the seasonal cycle between SIF_yield and cloud cover/precipitation demonstrated that water stress in 2015 indeed had large effects on canopy photosynthesis by limiting the production of fluorescence. However, the high PAR and fPAR, and the resulting high APAR partly offset the negative impacts of water stress, leading to the smaller decrease of SIF compared with the large negative anomalies of precipitation and SIF_yield (figures 3(a), (f), and (h)). The results of the central and northern Amazon (Regions B and C in figure 1, respectively) and the entire basin are provided in supplementary figures S6–8. All regions exhibited smaller negative anomalies in SIF than in SIF_yield during the 2015 drought, although the difference was not as significant as that in the southeastern Amazon. The spatial patterns of PAR, fPAR, APAR, and SIF_yield anomalies are provided in figure 4. Basin-wide negative anomalies were observed in SIF_yield, while large parts of the Amazon (the central and southern Amazon) were accompanied with high PAR and fPAR, and thereby high APAR.

The higher PAR during the drought resulted from lower cloud cover (figure 3(e), supplementary figures S6(e), S7(e), and S8(e)). The higher fPAR during the drought could be explained by the variations of LAI (supplementary figure S9). The LAI increased in the majority of the drought-affected areas, which synchronized with the availability of higher solar radiation. This is closely related to the exchange strategy between older leaves that are photosynthetically less efficient and new leaves that are photosynthetically more efficient in Amazon forests with leaf-exchanging
evergreen trees, resulting in a gradually increasing LAI over several months during the ascending phase of the seasonal cycle (Goulden et al. 2004, Mulkey et al. 2012, Myneni et al. 2007, Wu et al. 2016). This strategy enhances photosynthetic gain when solar radiation is abundant and the deep-rooted trees may not be seriously disturbed by the drought and are still well hydrated (Myneni et al. 2007). In contrast to the deep-rooted trees, some dry savannas, located in the east of Brazil (Region D in figure 1), showed declines in photosynthesis during the drought. LAI changes in these savannas were concordant with water variation, and the lower LAI during the drought resulted in lower fPAR (figure 5). A previous study (Myneni et al. 2007) reported that the phenological cycle of LAI in Amazon forests was timed to the seasonality of solar radiation, with higher leaf area during the shorter dry season when solar radiation loads were high. The LAI changes in the adjacent grasslands and savannas in Brazil were concordant with rainfall data. It should be noted that the LAI product contains significant uncertainty (Fang et al. 2012), and the future availability of LAI data products with higher accuracy will help us better understand the responses of Amazon ecosystems to drought.

3.3. Spatial variations of SIF\(_{\text{yield}}\) and SIF across the Amazon during drought

The monthly SIF\(_{\text{yield}}\) anomalies showed positive correlation with precipitation anomalies in the southeastern (\(r = 0.57, p < 0.0001\)), central (\(r = 0.59, p < 0.0001\)), and northern Amazon (\(r = 0.61, p < 0.0001\)) (figure 6(a)); the monthly SIF\(_{\text{yield}}\) anomalies showed negative correlation with VPD anomalies in the southeastern (\(r = -0.61, p < 0.0001\)), central (\(r = -0.42, p < 0.0001\)), and northern Amazon (\(r = -0.41, p < 0.0001\)) (figure 6(b)). These results suggested that the water stress could lower the SIF\(_{\text{yield}}\) to varying degrees across the Amazon. At the annual scale, the SIF\(_{\text{yield}}\) anomalies showed stronger correlations with precipitation anomalies in all the three regions (southeastern: \(r = 0.96, p < 0.0001\); central: \(r = 0.83, p = 0.012\); northern: \(r = 0.71, p = 0.048\)) (figure 6(c)). The correlation between SIF\(_{\text{yield}}\) and VPD anomalies was stronger at the annual scale (\(r = -0.80, p = 0.018\)) than at the monthly scale in the southeastern Amazon, and was similar in the other two regions (figure 6(d)). The SIF\(_{\text{yield}}\) was more sensitive to water stress in the southern Amazon especially at the annual scale. This was similar to the responses of other vegetation biophysical variables (e.g. NDVI, and EVI) to precipitation in the

Figure 4. The spatial distribution of anomalies of (a) PAR, (b) fPAR, (c) APAR, and (d) SIF\(_{\text{yield}}\) in 2015 relative to the means over the period of 2007–2014 in the Amazon.
Figure 5. The mean seasonal cycles of (a) precipitation, (b) PAR, (c) P enrichment, (d) LAI, (e) SIF, and (f) SIF yield for the dry savanna in the east of Brazil (Region D in supplementary figure 1). The multi-year means over the period 2007–2014 are shown in black lines with circles, and the 2015 values are shown in red lines with plus symbols.

Figure 6. Relationships between the SIF yield anomalies and climate variable anomalies in different regions at monthly and annual scales. (a) Monthly SIF yield anomalies versus precipitation anomalies; (b) monthly SIF yield anomalies versus VPD anomalies; (c) annual SIF yield anomalies versus precipitation anomalies; and (d) annual SIF yield anomalies versus VPD anomalies. The correlation coefficients (r) and associated p values provided in each figure were calculated by pooling together all the data in the three selected regions.
Amazon found in previous studies (Hilker et al. 2014, Lee et al. 2013, Xu et al. 2015). The SIF$_\text{yield}$ was influenced by temperature and water stresses that control LUE (Meroni et al. 2009, Van der Tol et al. 2014). In the Amazon region, temperature is generally not considered as a limiting factor of vegetation conditions (Nemani et al. 2003), and the LUE therefore largely depends on the variation of water stress. In northern parts of the Amazon with everwet conditions, vegetation phenology is more in phase with radiation, while precipitation is a major driver of vegetation phenology in southern counterparts with different lengths of dry seasons (Bradley et al. 2011). Therefore, LUE and SIF$_\text{yield}$ were more sensitive to water variability in the southern regions.

The impacts of the 2015 drought on SIF$_\text{yield}$ and SIF were further analyzed by examining their spatial variations and temporal evolutions throughout the four seasons (figure 7). Precipitation showed moderate declines in JFM and AMJ seasons in the central, eastern, and southern Amazon. Precipitation deficit began to aggravate in JAS, and showed the largest negative anomalies in OND when the drought affected nearly the entire Amazon basin. The extensive increase of VPD synchronized with the decline of precipitation throughout the seasons. Consequently, the SIF$_\text{yield}$ showed moderate declines in the first two seasons and large negative anomalies in JAS and OND due to the severe water stress. The SIF also showed similar spatial patterns throughout the year, but the drought had smaller impacts on SIF than on SIF$_\text{yield}$ in terms of magnitude and spatial extent of negative anomalies.

4. Conclusions

By making use of satellite SIF products along with other climate and vegetation datasets, we examined the impacts of the 2015 drought on the photosynthesis of Amazon forests to understand how radiation and precipitation jointly control photosynthesis. The SIF integrates information from SIF$_\text{yield}$, fPAR, and PAR, and is effective for diagnosing the photosynthesis status of Amazon forests. Satellite-based SIF products not only have significant potential for estimating GPP over large scales, but can also shed light on the relative influences of water and light availability on plant photosynthesis. Our results showed that in spite of severe dry conditions from August to December in 2015, the decrease of photosynthetic activity of the Amazon forests was not as high as expected because the high PAR, LAI, and fPAR partly offset the negative effects of water stress on photosynthesis. Our research indicates functional complementation...
between precipitation and solar radiation on the photosynthesis of Amazon forests, and also reveals that rainforests and savannas have different vulnerabilities to climate change.

Author contributions

J Xiao and X Li designed the research. X Li processed the data. X Li, J Xiao, and B He analyzed the data. X Li and J Xiao wrote the paper. B He provided comments and suggestions on the manuscript.

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