ORBITAL CHLOROPHYLL FLUORESCENCE AS A PROXY FOR PHOTOSYNTHESIS SEASONALITY AND STRESS AT THE CAATINGA

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ABSTRACT

Chlorophyll a fluorescence is emitted from photosynthesizing plants with peaks at the red and far-red frequency regions, and it relates directly to photosynthesis yield and stress. Recent developments in remote sensing allow us to estimate Sun-induced fluorescence (SIF) from plants on the Earth's surface. In this study, we have used SIF from the GOME-2 orbital instrument to characterize the usual seasonal variation of fluorescence and to study vegetation responses to anomalous droughts. Results show that GOME-2 SIF at both frequencies responded consistently to temperature and precipitation variations observed, and document a near halving of emissions in response to a drought observed there from 2012 to 2016. SIF was positively correlated to EVI, NDVI and GPP but correlations were influenced by vegetation structure and temporal aspects pertaining to each variable.

Key words *– Chlorophyll Fluorescence, Ecology, Vegetation Indexes, Carbon Flux, Abiotic Stress.*

1. INTRODUCTION

Among the plethora of methods that can be used to assess plant physiology, the remote sensing of vegetation responses offers great advantage over field techniques in regard to the size of the population that can be sampled in a given time interval. Although fluorometers used to investigate chlorophyll fluorescence at the leaf-level can provide a number of specific responses through controlled exposure to light [1], only light-adapted, or steady-state, fluorescence emissions can be studied remotely with current technology at landscape-level. This emission is termed Sun-induced chlorophyll fluorescence (SIF) and, despite its limitations when compared to the leaf-level fluorescence parameters (*e.g.*, F_v/F_m, NPQ, qE) it can be used to infer the instantaneous photosynthetic rate and to detect and qualify the influence of diverse abiotic factors in the photosynthetic apparatus of plant populations, such as drought, low temperature, pollutants and mineral nutrition [2, 3].

While other vegetation indexes - such as the Normalized Difference Vegetation Index (NDVI), the Photochemical Reflectance Index (PRI) and the Enhanced Vegetation Index (EVI) - are capable of providing information about abiotic stress effects by observation of leaf pigment composition and structural changes to vegetation; chlorophyll fluorescence is more sensitive to environmental changes and can show the presence of stress before it has caused alterations to the plants that would be detectable by other remotely-sensed vegetation indexes [4, 5]. Chlorophyll fluorescence is the parameter most directly related to photosynthesis that can be remotely measured with current technology [2, 3].

Fluorescent photons are emitted from chlorophyll molecules at both photosystems I and II (PS I and PS II), with PS II signal dominating the red region of the spectra ($\lambda = 685nm$) and PS I signal partially overlapping that of PS II in the far-red region ($\lambda = 730 - 740nm$). The contribution of PS I to the far-red/near-infrared SIF (SIF_{FR}) varies from 30 to 45% at steady-state, between known agricultural species [6]. While the PS I fluorescent emissions are generally considered to be stable under moderate stress, PS II fluorescence responds markedly to environmental variations and stress [6, 7]. Previous studies on red and far-red SIF (SIF_R and SIF_{FR}) have found differences on the relationships between these two fluorescence emissions and climate, that depended greatly on vegetation structure and composition, and suggested that more studies investigating SIF at both frequencies, from heterogeneous vegetation, were necessary to improve our understanding on the relationships between SIF, GPP, phenology and vegetation stress [7–9].

Therefore, we have chosen to study SIF estimates by the GOME-2 orbital instrument from heterogeneous vegetation at the Caatinga's dry forests and steppes, where conditions favor the study of photosynthesis under a harsh seasonal cycle of environmental variation and also the study of sustained responses to extreme climate. Accordingly, our specific objectives were to describe seasonal patterns of chlorophyll fluorescence dynamics as estimated by the GOME-2 orbital instrument in a ten-year period and to model the observed SIF_R and SIF_{FR} as functions of environmental parameters, testing their responses to the climate's seasonal variation and to any identifiable period of anomalous climate; and finally, to compare the observed SIF dynamics under these conditions to other, well-known, remotely sensed vegetation parameters like EVI and NDVI, as well as with seasonal dynamics of gross primary production (GPP) estimated through modern methods.

2. MATERIAL E METHODS

2.1. Study area

The Caatinga ecoregion is located on an arid region in the northeastern part of Brazil. Despite the relatively rich soils with high *ph* level normally found in this quaternary region, the vegetation has lower productivity than average tropical formations and is adapted to endure a long seasonal drought generally lasting for half of the yearly cycle. Caatinga's vegetation is mostly comprised of dry forests, steppe-savanna and thorny shrub-lands rich in Cactaceae. Forest formations are deciduous many local species present thorns. Despite dry conditions and strong seasonality regarding water availability, fire does not play a significant role in these forests' dynamics [10, 11].

Four sample sites were chosen based on existing preservation areas at this biome and were delimited with the aim of including the largest possible area of natural vegetation with minimal contamination by agriculture and other human activities.

2.2. Sun-Induced Fluorescence - SIF

Considering our aims, we chose the Global Ozone Monitoring Experiment 2 (GOME-2) because it supplies red and far-red SIF data at the landscape level, because it samples from the whole surface of the Earth continuously, and finally, because it has the longest sampled time-series among all available orbital SIF sources [12–14]. GOME-2 SIF data was downloaded from NASA's Aurora Data Validation Center (ADVC) at version 2.7 for SIF$_{FR}$ and 2.6 for SIF$_R$ (the latest versions of each, respectively). The period we chose to study comprises most of GOME-2 available data and it spans ten years, from 2007/01 to 2016/12 for SIF$_{FR}$ and from 2007/02 to 2015/12 for SIF$_R$. Since SIF emission depends on Photosynthetically Active Radiation (PAR), and PAR incidence changes with latitude and the Earth's movement around the sun, in this study we have used PAR-normalized SIF$_{FR}$ and SIF$_R$ to improve the comparability of fluorescence measured from different latitudes and dates. This is obtained by dividing the measured absolute SIF$_{FR}$ (SIF$_{aFR}$), and absolute SIF$_R$ (SIF$_{aR}$), by the cosine of the Sun's zenith angle at the place and time of measurement. This has been shown to have a normalizing effect on the seasonal variation of PAR incidence [13, 15].

2.3. Environmental Indicators

To cover the basic temperature and water-availability aspects of environmental characterization we used Land Surface Temperature (LST) and Precipitation Rate data. Land surface temperature from the MODIS instrument (MOD11C3, version 6), combining day and night LST monthly averages from 2007/01 to 2016/12, and monthly Precipitation rate from the Tropical Rainfall Monitoring Mission (TRMM - TMPA 3B43, version 7), from 2007/01 to 2016/12.

2.4. Vegetation Indexes

To investigate the coherence of PAR-normalized fluorescence with seasonal phenological processes know to affect SIF emissions (chiefly, chlorophyll degradation and leaf shedding) we have employed EVI and NDVI from MODIS (MOD13C2, version 6) at the monthly temporal resolution, covering the same period as the SIF data: from 2007/01 to 2016/12.

2.5. Gross Primary Production - GPP

Fluorescence has been suggested as parameter with potential to improve estimates of Gross Primary Production [16–19]. Therefore, to investigate the relationship between productivity and steady-state, remotely-sensed, chlorophyll *a* fluorescence we chose to use FLUXCOM GPP [20, 21] at the monthly temporal resolution. FLUXCOM data from 2007/01 to 2013/12 was used as this is the maximum overlapping period between the GOME-2 SIF and the FLUXCOM GPP data sets. Since GPP is PAR-normalized, correlation tests with SIF at both frequencies were done using, non-PAR-normalized, absolute SIF at the red and far-red frequencies (SIF$_{aR}$ and SIF$_{aFR}$, respectively) to decrease bias between these variables.

3. RESULTS AND DISCUSSION

3.1. SIF seasonality and climate

The climate's influence over the seasonality of GOME-2 SIF at both frequencies can be inferred from STL seasonal components (Fig. 1). SIF$_R$ is efficiently re-absorbed by chlorophyll molecules [3] and so, the seasonal discrepancy between the emission of SIF at each frequency (Fig. 1) is in agreement with variations in re-absorption of SIF$_R$ due to phenological cycle seasonality.

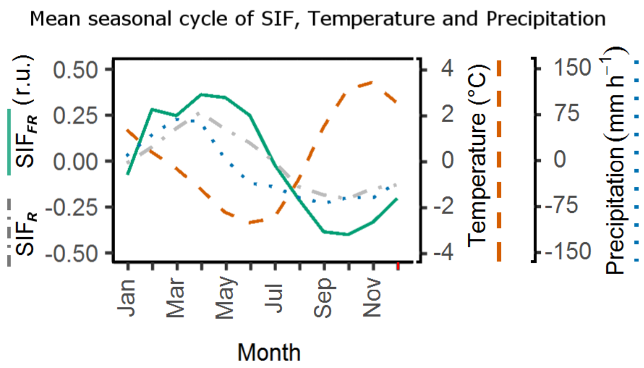

Figure 1: Mean seasonal components of SIF$_R$, SIF$_{FR}$, Temperature and Precipitation, from 2007 to 2016.

Mean monthly SIF per site was modeled in GLMMs as a function of land surface temperature, precipitation rate and the factor *Date* (months nested within years), with *sample-sites* used as a random factor. Results showed strong effects of these variables on fluorescence at the Caatinga vegetation for both SIF$_{FR}$ and SIF$_R$ but not for their ratio, SIF$_R$/SIF$_{FR}$ (Tab. 1). The factor *Date* (year/month) was significant only to SIF$_{FR}$ but the interaction terms *"Precip : Date"* were significant for SIF at both frequencies, suggesting the influence of anomalous precipitation during the studied period. The effect of surface temperature over SIF$_R$ and SIF$_{FR}$ was relatively larger than that of precipitation rate at this biome and *Temperature* was the fixed effect nearer to significance for SIF$_R$/SIF$_{FR}$ (Tab. 1).

3.2. SIF and the 2012 drought

Results have shown a clear response to the 2012 drought event, when SIF$_{FR}$ yearly average dropped to 50.43% of the previous year's level, or to 54.71% of the 2007-2011 period's average. Comparatively, SIF$_R$'s yearly average dropped to 65.25% of 2011 levels and to 74.81% of the 2007-2011 period's average.

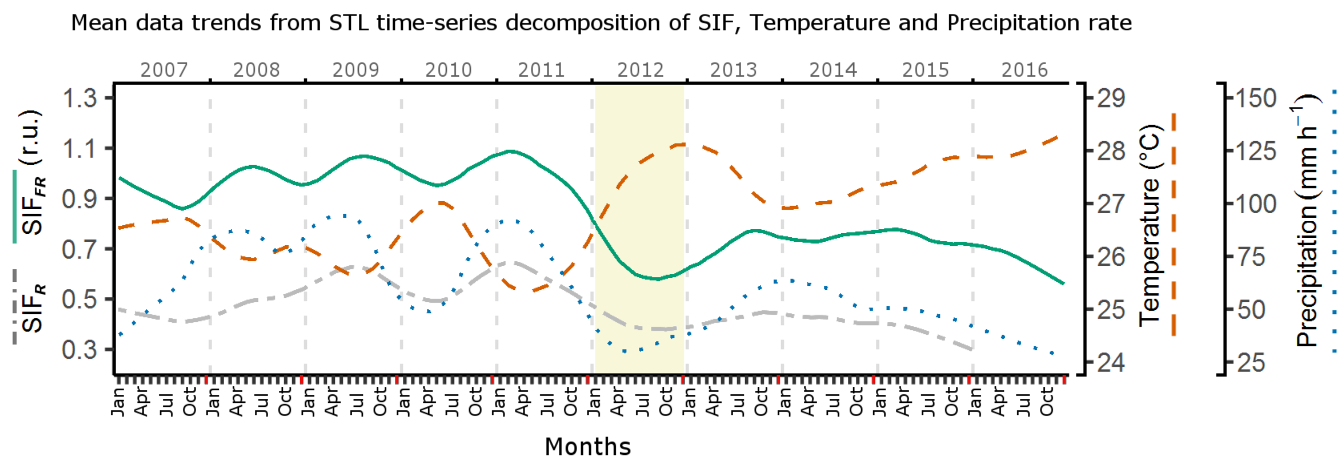

Figure 2: Data-trends of SIF$_R$, SIF$_{FR}$, Temperature and Precipitation, from 2007 to 2016.

Caatinga - GLMM of SIF and Climate				
Variable	**Fixed effects**	**Coef.**	**d.f.**	***p* value**
SIF$_{FR}$	Precipitation	0.128	1	<0.001***
	Temperature	-0.293	1	<0.001***
	Date	-0.001	1	<0.001***
	Precip : Temp	0.008	1	0.172
	Precip : Date	0.001	1	0.019*
	Temp : Date	0.001	1	0.004**
	Precip : Temp : Date	0.000	1	0.477
SIF$_R$	Precipitation	0.063	1	<0.001***
	Temperature	-0.125	1	<0.001***
	Date	0.000	1	0.162
	Precip : Temp	0.000	1	0.633
	Precip : Date	0.001	1	<0.001***
	Temp : Date	0.000	1	0.259
	Precip : Temp : Date	0.000	1	0.738
SIF$_R$/SIF$_{FR}$	Precipitation	-0.022	1	0.970
	Temperature	0.023	1	0.161
	Date	0.000	1	0.376
	Precip : Temp	-0.005	1	0.676
	Precip : Date	0.000	1	0.384
	Temp : Date	0.000	1	0.943
	Precip : Temp : Date	0.000	1	0.900

Table 1: GLMM results: "Temp" is surface temperature, "Precip" is precipitation rate and "Date" is a factor with months nested into years. SIF$_{FR}$ has $n = 480$, SIF$_R$ and their ratio have $n = 428$.

Regardless of SIF emission at different frequencies, the 2012 event has been documented as the worst drought in 38 years at the Caatinga, and fluorescence emission dynamics observed with GOME-2 SIF agree with previous leaf-level observations about the decrease in photosynthetic output and productivity at the Caatinga on that year [22, 23]. Furthermore, our data showed the continuing impact of drought in the region, when mean SIF from 2012 to 2016 was only 65.86% of what was observed before this drought, on the period from 2007 to 2011.

The frequency and severity of such drought events is predicted to increase under the ongoing climate change [23] and therefore, SIF responses to the extreme drought of 2012 and the subsequent years of milder drought (Fig. 2) suggest that the carbon exchange dynamics at the region could undergo a significant change.

3.3. VIs and GPP

Chlorophyll fluorescence from GOME-2 was positively correlated to EVI, NDVI and GPP at the sampled Caatinga vegetation on both red and far-red frequencies (Tab. 2). Nevertheless, SIF$_R$/SIF$_{FR}$ was not significantly correlated to any of the variables tested but was instead, negatively correlated to GPP at a nearly significant level.

Correlation between SIF, EVI, NDVI and GPP.			
Variable	**Corr. Variable**	**PPMC**	***p* value**
SIF$_{FR}$	EVI	0.81	<0.001 ***
SIF$_{FR}$	NDVI	0.79	<0.001 ***
SIF$_{aFR}$	GPP	0.51	<0.001 ***
SIF$_R$	EVI	0.68	<0.001 ***
SIF$_R$	NDVI	0.66	<0.001 ***
SIF$_{aR}$	GPP	0.50	<0.001 ***
SIF$_R$/SIF$_{FR}$	EVI	0.00	0.972
SIF$_R$/SIF$_{FR}$	NDVI	0.00	0.962
SIF$_{aR}$/SIF$_{aFR}$	GPP	-0.20	0.073

Table 2: Results from Pearson rank-correlation tests between SIF and EVI/NDVI/GPP.

Vegetation indexes represent a measure of chlorophyll content and phenological development, therefore, they should relate directly to potential photosynthesis (photosynthetic capacity) but not necessarily to actual, instantaneous, photosynthetic yield. Furthermore, the phenomena influencing variation in vegetation indexes (*e.g.*, leaf abscission and flush, chlorophyll synthesis or degradation) happen slowly (days) in relation to chlorophyll fluorescence variation (milliseconds).

The correlation discrepancies between GOME-2 SIF and FLUXCOM GPP observed here (Tab. 2) are also related to the temporal effect discussed above. The FLUXCOM monthly GPP dataset is based on GPP estimations with an 8-day temporal resolution and therefore it is inherently different from a monthly average of SIF measured at a specific time of day (GOME-2 SIF is always estimated at 09:30 solar time). Furthermore, the upscaling process through which FLUXCOM GPP is produced from FLUXNET's field data on carbon fluxes, takes both vegetation indexes used here as inputs (MODIS EVI and NDVI), further biasing the data's temporal resolution for comparisons with GOME-2

SIF. We believe that correlation between SIF and GPP is also influenced by the fact that field measurements of carbon-flux from South America are lacking in both spatial distribution and frequency therefore, it is not surprising that the Caatinga is reported as an area with uncertainties in the reliability of carbon-flux and productivity estimates [24].

4. CONCLUSIONS

Results demonstrate the sensitivity of GOME-2 fluorescence to climate, supporting predictions that SIF_{FR} and SIF_{R} must show seasonality and responses to abiotic influence even when measured at the landscape level [3, 8, 25]. To our knowledge, this is the first study to show such responses from orbital estimates of SIF at both the red and far-red frequencies, and from such heterogeneous communities.

Our results also suggest that GOME-2 SIF more adequately represents the productivity dynamics of the vegetation at these regions of South America than FLUXCOM GPP, regarded as one of the best approximations into global productivity to date. Hence, we agree with previous observations that SIF, as a direct proxy into the photosynthetic activity, should be used to constraint modeling of GPP [16–19].

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