TRACKING WATER LIMITATION IN PHOTOSYNTHESIS WITH SUN-INDUCED CHLOROPHYLL FLUORESCENCE

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ABSTRACT

Sun-induced chlorophyll fluorescence has a mechanistic link to photosynthesis. It is therefore sensitive to subtle, stress-induced changes in photosynthetic activity. This study shows the evolution of the emission of sun-induced chlorophyll fluorescence (SIF) by a yellow mustard stand grown in plant boxes under varying water supply and under varying meteorological conditions, causing changes in the evaporative demand. Affected by both leaf biochemical processes and by changes in the plant canopy structure, we combined the fluorescence measurements with reflectance measurements to assess the effect of both components. A first result of this study shows that the biochemical component of the fluorescence emission decreases because of either a reduction in the water supply or an increase in the evaporative demand by the atmosphere.

Index Terms— *Solar-Induced chlorophyll fluorescence, drought stress, soil water availability, fluorescence yield*

1. INTRODUCTION

Because of its mechanistic link to photosynthesis, sun-induced chlorophyll fluorescence (SIF) is a promising tool for stress monitoring. The process of fluorescence emission occurs at the photosystem level, while SIF is observed at the canopy level. Photosystem-level fluorescence is sensitive to various stresses [1]. However, many questions arise concerning the interpretation of SIF at the canopy scale, as various canopy-scale processes, such as scattering and reabsorption, interfere with the signal [2]. Drought stress is known to affect the plant both the photosystem level (e.g., by increasing the non-photochemical quenching (NPQ)) and the canopy level (e.g., by leaf rolling, changing the canopy scattering). The relative importance of each of these processes alters throughout the fluorescence emission spectrum. Consequently, it is interesting to study the SIF emission at 760 nm (SIFA) and at 687 nm (SIFB) and their reaction to drought stress separately [3]. This paper shows a field experiment in which mustard grew under increasing stress conditions. At the same time, the soil water availability, various vegetation indices, thermal emission and various meteorological variables were measured. The impact of a decrease in soil water availability on SIFA and SIFB is described, while the ancillary measurements are used to identify the driving forces of the change in SIFA and SIFB emission.

2. FIELD EXPERIMENT

Yellow mustard (*Sinapis alba*) was grown in two plant boxes, located in Selhausen (50°52'09.3"N, 6°27'05.6"E), Germany. The plant boxes had a size of 2 m x 2 m and had a depth of 40 cm. At the bottom, the boxes had a drainage layer, draining the excess water. Both boxes were subject to different irrigation regimes, in which one of the boxes got more irrigation water (figure 1). The FloX field spectrometer (JB Hyperspectral, Düsseldorf, Germany) was installed on a tower with 4 m height over one of the plant boxes. The FloX was installed with an observer zenith angle of 90°. The mustard was sown on DOY 230. Between DOY 283 and DOY 293, a gradual stress was applied to one of the two boxes. Between DOY 294 and DOY 317, the FloX pivoted between the two plant boxes. Water availability was measured by means of soil moisture sensors (5TE and 5TM, Metergroup, USA). In addition, soil water potential was measured with Teros 21 soil water potential sensors (Metergroup, USA).

Fig. 1. FloX measuring SIF emission of yellow mustard growing in plant boxes. The plant box on the left received less irrigation water compared to the box on the right.

3. DATA ANALYSIS

3.1. Analysis of SIF data

Top of canopy-SIF comprises four components, being the incident photosynthetically active radiation iPAR, the fraction of the absorbed radiation that is absorbed by chlorophyll $fPAR_{Chl}$, the fluorescence emission ϵ and the probability of a photon leaving the observed direction σ (Equation 1). Both ϵ and σ are wavelength-specific variables.

$$\text{SIF} = \text{iPAR} \cdot \text{fPAR}_{\text{Chl}} \cdot \epsilon \cdot \sigma \tag{1}$$

In case of a drought stress, we expect changes in both ϵ and σ. In addition to ϵ we also use the SIF yield (SIFY) to evaluate the effect of stress on SIF emission. This is equivalent to the SIF normalized by iPAR (Equation 2).

$$\text{SIFY} = \frac{\text{SIF}}{\text{iPAR}} = \text{fPAR}_{\text{Chl}} \cdot \epsilon \cdot \sigma \tag{2}$$

In the case of SIFA, Yang et al. (2020) [4] proposed the Fluorescence Correction Vegetation Index (FCVI) that could serve as a surrogate for the product of $fPAR_{Chl}$ and σ, allowing for a separation of the physiological and structural component of the SIF signal. FCVI is the difference between near-infrared reflectance close to the 750 nm band (R_{750}) and the broadband reflectance in the chlorophyll absorption spectrum (R_{VIS}) (Equation 3). In the case of SIFB, σ is subject to reabsorption of emitted radiation by overlying chlorophyll molecules and canopy scattering. Consequently, σ is harder to calculate in that case. In this case, we assess the contribution of σ by means of more conventional vegetation indices.

$$\text{FCVI} = R_{750} - R_{VIS} = \text{fPAR}_{\text{Chl}} \cdot \sigma \tag{3}$$

3.2. Assess drought stress conditions

Drought stress contains two aspects, being water supply and evaporative demand. The water supply was evaluated using the soil water content and soil water potential data. The evaporative demand was provided for using the potential grass reference evapotranspiration (ET0) served as a proxy for the evaporative demand. Following the Pennman-Monteith approach, the latter variable takes the effect of vapour pressure deficit, wind speed, solar irradiation and air temperature into account [5].

4. FIRST RESULTS

4.1. Effect of soil water availability on SIF

Figure 2 shows the evolution of SIF, SIFY and ϵ under increasing drought stress conditions, with a recovery from the drought stress in the end. The decrease in SIFA between DOY 284 and DOY 288 is consistent with the idea that SIFA can serve as a proxy for photosynthetic activity, which

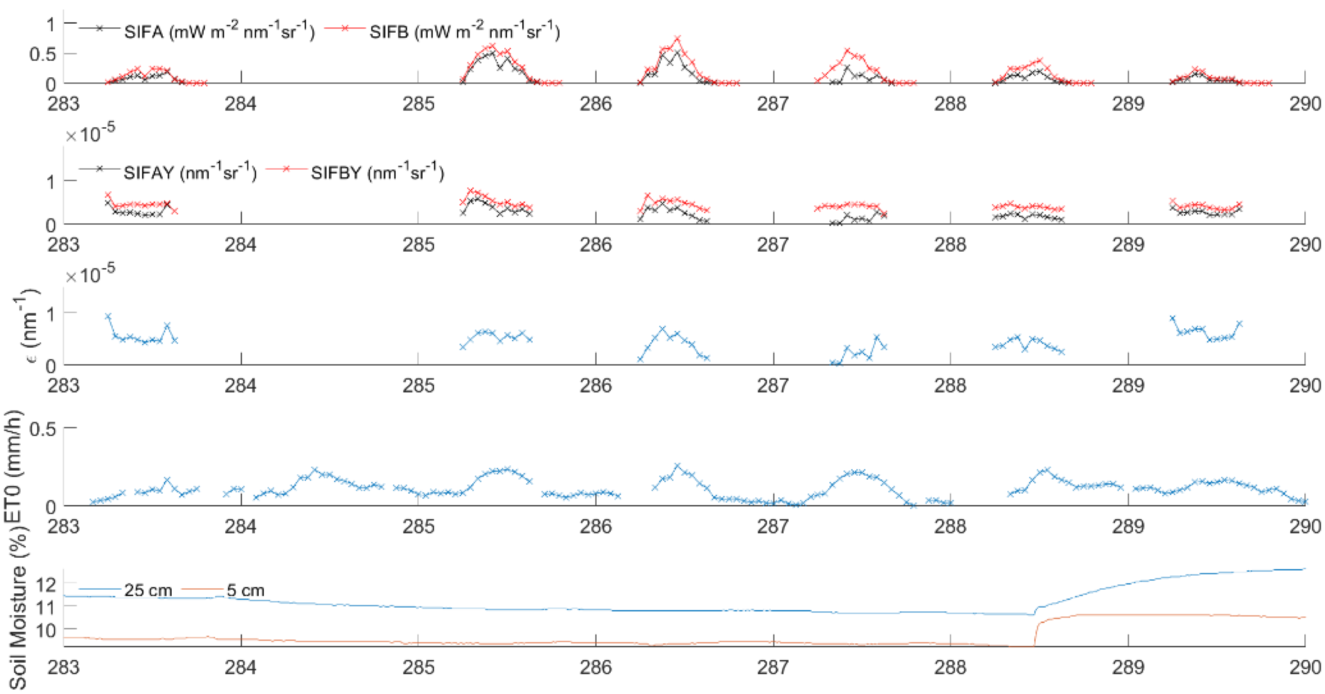

Fig. 2. Evolution of the SIF, SIFY at the O_2-A and the O_2-B band nm and ϵ at the O_2-A band under increasing drought stress conditions with a pulse of irrigation water at the end. Soil moisture was measured at 5 and 25 cm depth.

decreases in case of a stress. This decrease was most notable in the morning, as an increase in NPQ under stress conditions causes a decrease in fluorescence emission [6]. The decrease in SIFA translates itself to a decrease in ϵ, suggesting that there is a plant physiological driver behind this reaction. The increase in water availability in DOY 289 was followed by a prompt increase in ϵ. It is worth noting that ϵ was more variable during the morning hours compared to the afternoon. During the period of intensifying stress, the difference between SIFA and SIFB decreased. Wieneke et al. (2016) [7] attributes this effect to a change in plant structure.

4.2. Effect of evaporative demand on SIF

Figure 3 shows a cross plot of the ET0 at noon measured during the entire campaign. In the lower edges (ET0<0.4 mm/h), SIFA emission increased linearly with ET0, as an increase in irradiation increases both variables. At ET=0.4 mm/h, SIF reaches its plateau around 0.5 $mWm^{-2}sr^{--1}nm^{-1}$. This behaviour holds for both SIFA and SIFB. Consequently, SIFY decreases in high light conditions. Similarly, an increase in ET0 in this region goes with a drop in ϵ, indicating that the fluorescence becomes less efficient in case of a high ET0. This is consistent with the idea that NPQ is the most important plant protection mechanism, and that its relative importance increases in cases of drought stress.

5. DISCUSSION

The Fluorescence Explorer (FLEX) satellite will be the first of its kind designated to measure SIF at the global scale, measuring at both the 760 nm and 687 nm band. By characterizing the reacting of SIFA and SIFB to drought stress, we contribute to a proper interpretation of FLEX data in the context of drought stress monitoring. Given the sensitivity of the ϵ to the soil moisture and ET0, we believe to be able to detect a plant physiological signal at the canopy scale. Comparing SIFA to SIFB data is to provide additional information concerning plant stresses, as stress induces a different behaviour across the fluorescence emission spectrum. A careful analysis of the relationship between soil water availability, SIF emission and reflectance is expected to improve our understanding of the effects of stress on fluorescence and on how to use SIF as an early drought diagnostic.

6. CONCLUSION

Because of its mechanistic link to photosynthesis, SIF observations can be linked to a plant stress. Drought stress contains of two components: soil water availability and atmospheric water demand. The SIF emission shows different reactions at 760 nm and at 687 nm bands. The reaction of canopy-scale SIF is driven by a combination leaf biochemical and canopy structural changes. SIFA band was more reactive to changes in soil moisture or ET0 compared to SIFB.

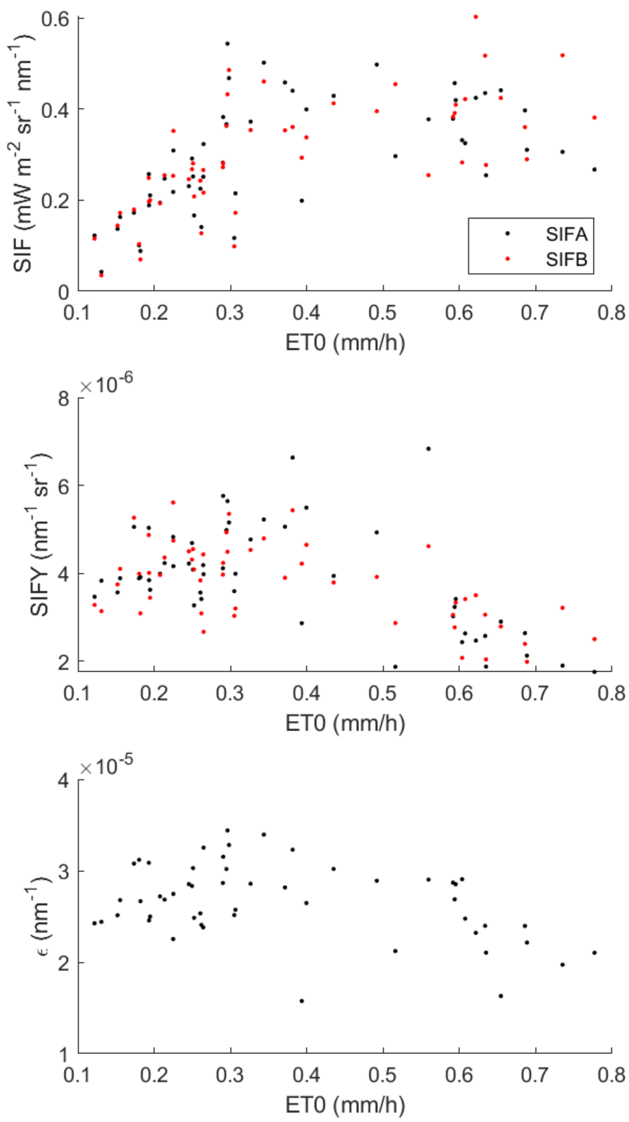

Fig. 3. Cross plots with hourly averaged ET0 around noon and hourly averaged SIF (upper plot), SIFY (middle plot) and ϵ (lower plot) around noon, taken over the course of the entire experiment

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