ANALYSIS OF ALONG-TRACK PROFILES OF SUN-INDUCED CHLOROPHYLL FLUORESCENCE DERIVED FROM HYPERSPECTRAL IMAGING DATA

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ABSTRACT:

Remote sensing of sun-induced chlorophyll fluorescence is a promising approach to track photo-synthetic activity at various scales. So far, knowledge on the spatial patterns of the signal is very limited. In this study, we investigate the possibility to derive sun-induced chlorophyll fluorescence over an intensive agricultural area by means of airborne hyperspectral data. Main focus of the analysis is to interpret the spatial variability of the estimated fluorescence signal on the basis of its interdependency with different proxies for green vegetation. Results indicate that the fluorescence signal has potential to explain intra-field variations concerning vegetation state and cover.

1. INTRODUCTION

A significant amount of the gas exchange between the terrestrial bio-geosphere and the atmosphere is mediated by plants through photosynthesis (Ozanne et al., 2003). A better understanding of the spatiotemporal variability of photosynthetic rates is indispensable, e.g. to explore and quantify terrestrial carbon fixation by plant ecosystems (Damm et al., 2009). Remote sensing (RS) offers the unique possibility to monitor vegetation productivity in a spatially explicit way (Hilker et al., 2008). Thereby, most of the information that has been gathered has come from reflected light in the solar domain (Moreno et al., 2006). An alternative to this approach is offered by the quantification of sun-induced chlorophyll fluorescence (Fs), which is considered a more direct probe of plant condition and functioning because of its direct relation to photosynthesis (Meroni et al., submitted, Rascher et al, 2009). Indeed, a part of the light absorbed by chlorophyll pigments is excluded from the light reactions of photosynthesis and re-emitted at longer wavelengths as fluorescent light (Meroni et al, submitted). In combination with the non-photochemical quenching (NPQ), a mechanism protecting the photosynthetic apparatus by safely dissipating excess energy as heat (Demming-Adams and Adams, 1996), chlorophyll fluorescence is an expression of the balance between light harvesting and light utilization in the photosynthetic process (Grace et al., 2007). Therefore, Fs is correlated to the energy used for photosynthesis and, thus, can serve as an indicator for photosynthetic efficiency (Rascher and Pieruschka, 2008).

Encouraged by the advance in sensor technology, research has recently focused on deriving information on sun-induced chlorophyll fluorescence by means of RS data (Hilker et al., 2008, Moreno et al., 2006, Rascher et al., 2009). However, the majority of this research was performed on the basis of ground level measurements. Studies on the spatial patterns of chlorophyll fluorescence, which are only possible when using air- or spaceborne data, are fairly rare (Meroni et al., submitted). Therefore, the present study investigates the possibility to derive Fs using airborne hyperspectral data. Three major goals are investigated: (1) To assess the spatial distribution of Fs for a set of selected cornfields (MC). The focus is on the variability between different fields (inter-field) and within individual fields (intra-field). (2) To compare the spatial patterns of Fs to that of different green vegetation proxies. And finally, (3) to identify possible external drivers for the variability in Fs values.

2. MATERIAL AND METHODS

Imaging spectroscopy data used in this work was acquired by the SIM.GA HYPER push-broom sensor during the CEFLES2 campaign on June 30, 2007. The VNIR spectrometer covers the spectral range from 400-1000 nm with 512 spectral bands and a spectral sampling interval of 1.2 nm. The HYPER image covers the Marmande study site, an extensive agricultural area in the Garonne river valley, South West of France. A comprehensive overview of the remote sensing component of CEFLES2 can be found in (Rascher et al., 2009).

Sun-induced chlorophyll fluorescence was derived using the Fraunhofer Line Discrimination (FLD) principle (Plascyk, 1975) according to modified equations from (Maier et al., 2003). The rationale behind this method is to decouple Fs from the reflectance background in correspondence to so-called Fraunhofer Lines, i.e. specific spectral lines characterized by very low levels of incident irradiance (Rascher et al., 2009). In short, the Fs in-filling was quantified by comparing the depth of the oxygen absorption line at 760 nm (O_2-A) of the vegetation target to that of a non-fluorescent bare soil reference (Figure 1). For the calculation of absorption depth, spectral measurements inside (λ_{IN}) and outside (λ_{OUT}) the absorption line were used. λ_{IN} was calculated as an average of two bands at the bottom of the O_2-A feature and λ_{OUT} was derived as the mean of 2×9 bands located at both flanks of the absorption line.

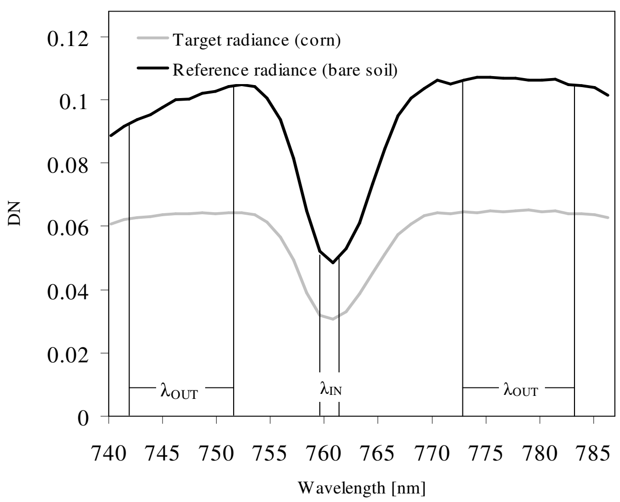

Figure 1: Detailed view of the oxygen absorption band at 760 nm as recorded by HYPER. Refer to the text for further explanations.

In addition to the Fs estimates, three different green vegetation proxies were calculated. The Simple Ratio (SR) and the Normalized Difference Vegetation Index (NDVI), which are essentially a measure of canopy greenness, and the fractional corn cover (FCC) derived from a spectral mixture analysis.

Deriving reliable Fs values turned out to be complex. The signal recorded by HYPER strongly varies across the track, i.e. perpendicular to the flight direction. Several view-angle dependant disturbing effects are important, including shifts in the width and position of spectral bands, atmospheric scattering and absorption as well as anisotropic surface reflectance. Moreover, the directionality of the Fs signal as emitted by canopies is still little understood. First attempts showed a strong cross-track Fs gradient. Moreover, Fs estimates proved to be sensitive to wavelengths and the choice of reference surfaces (e.g. differences between dark and bright soils) for the FLD method. For example, wide ranges for λ_{OUT} resulted in stable measurements, but used DNs might be additionally affected by trends in vegetation reflectance spectra (e.g. red edge). However, possible effects should be relatively little for study of single crops. Consequently, it was not possible to derive Fs values in physical units. Only a relative evaluation of Fs estimates using along-track profiles was feasible. These were represented by single image columns of the same viewing and illumination geometry. Furthermore, an unexplained degree of statistical noise caused by the uneven response of the sensor must be taken into account when evaluating the results.

3. RESULTS

Two distinct features can be observed when considering the along-track profile of Fs across the investigated cornfields (Figure 2). First, the magnitude of both unfiltered and filtered Fs signal varies throughout the transect in a way that allows to distinguish between different cornfields. Second, the unfiltered Fs signal is highly variable within individual cornfields. In particular MC12 stands out. Here, the intra-field variability of Fs seems to be higher than the average. Several major repetitive patterns can be observed within cornfields. Some show a relative constant Fs distribution (MC7, MC26), others are characterized by erratic patterns, e.g. a steady increase of Fs towards the field center (MC14b), intra-field Fs value gaps (MC14b) or a sudden leap of Fs values (MC8).

Field name	CV Fs	CV SR	CV NDVI	CV FCC	r^2 (Fs &. SR)	r^2 (Fs & NDVI)	r^2 (Fs & FCC)
MC14b	0.67	0.20	0.09	0.18	0.36	0.29	0.48
MC12	1.31	0.14	0.09	0.13	0.00	0.01	0.00
MC8	0.32	0.11	0.03	0.10	0.34	0.32	0.39
MC7	0.31	0.11	0.04	0.06	0.00	0.00	0.00
MC4	0.14	0.11	0.04	0.06	0.24	0.21	0.23
MC26a	0.21	0.06	0.02	0.05	0.00	0.00	0.00

Table 1: Coefficients of variation (CV) and coefficients of determination (r^2) for Fs, SR and FCC.

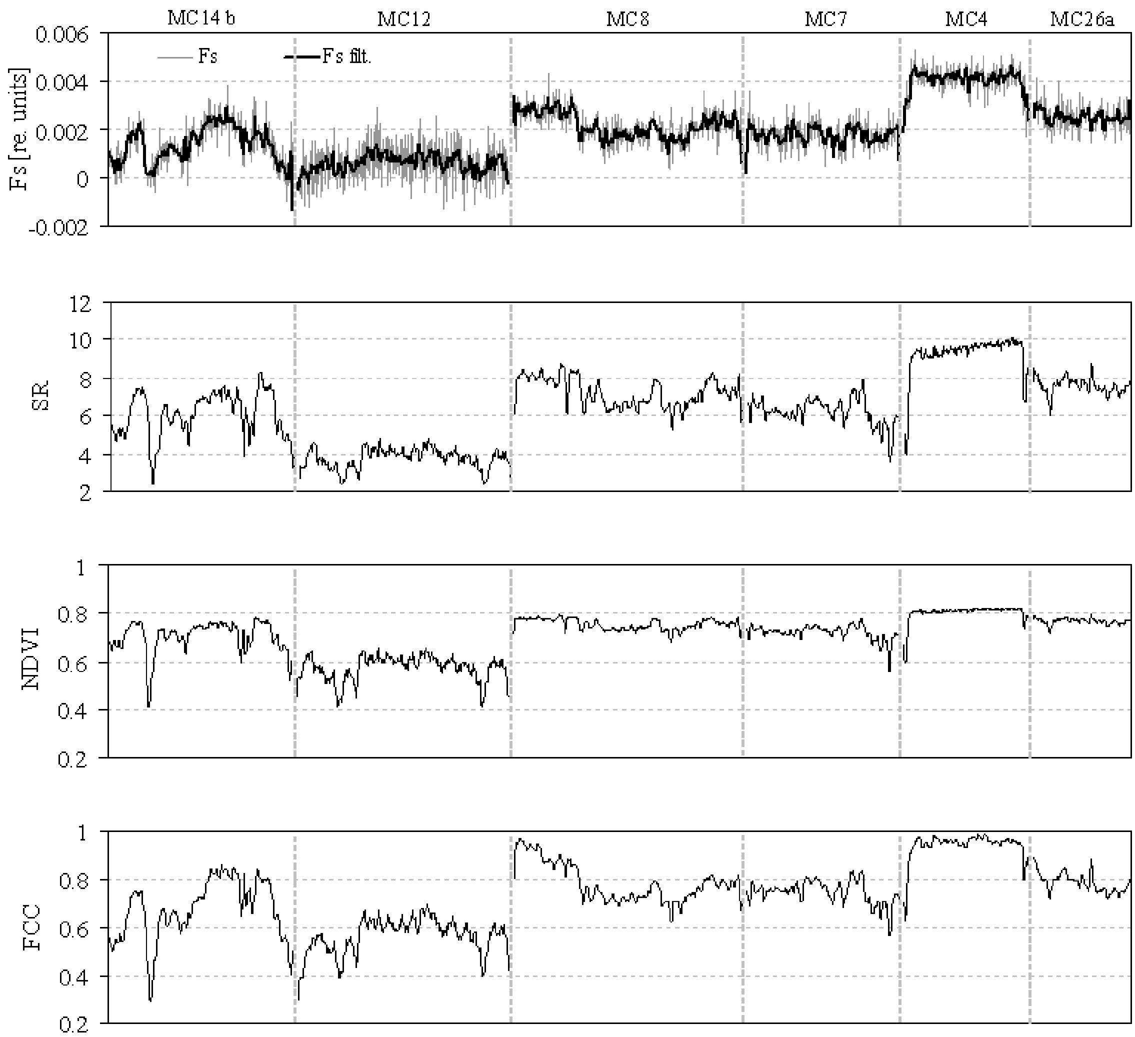

Figure 2: Along-track profiles of Fs, SR, NDVI and FCC across six investigated cornfields in the Marmande study area. The original Fs signal (grey) is overlaid with the filtered Fs signal (black, mean filter using 3 neighbouring values).

The spatial distribution of the Fs signal and the green vegetation estimates are approximately similar, i.e. similar erratic patterns within and between different cornfields can be found in all profiles. This indicates a strong dependency of Fs on the amount of green vegetation. However, two major differences can be observed: NDVI shows a somewhat lower variation caused by the saturation effect from values higher than 0.8. For example, no great differences can be observed between MC4 and MC26 for the NDVI, whereas great variations can be found between both fields in the other profiles. Second, compared to the vegetation proxies, the intra-field variability of the original Fs signal is clearly higher. This finding is corroborated by higher coefficients of variation (CV) for Fs, compared to the CV of the green vegetation estimates (Table 1).

The observations from the along-track profiles seem to be reasonable when taking the scatterplots into account (Figure 3). A strong positive dependency between Fs and the green vegetation proxies can be observed for both cornfield mean values and all pixel values of the profile. Two different kinds of relationships, a rather linear (SR, FCC) and a nonlinear (NDVI), can be identified.

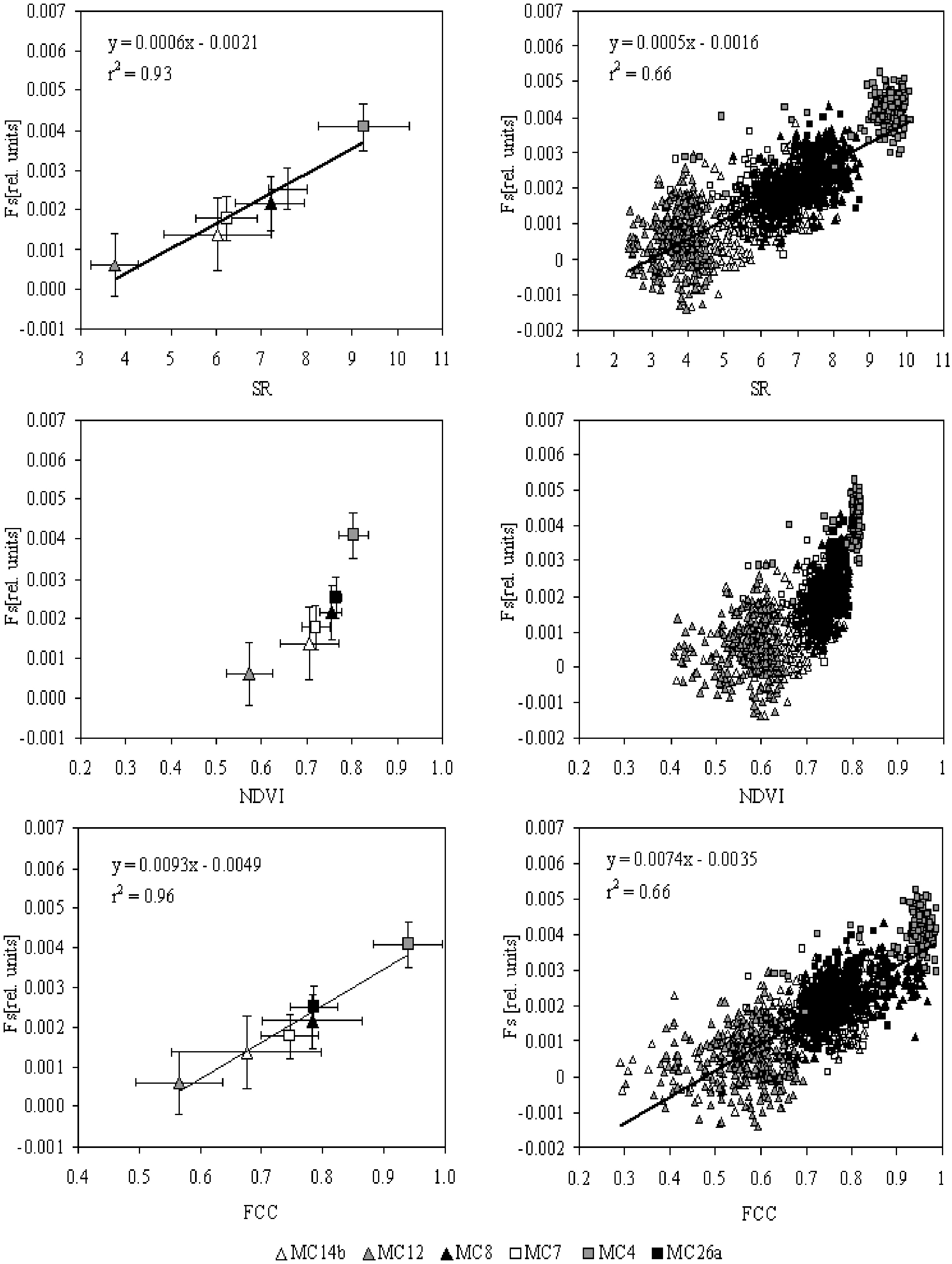

Figure 3: Relationship between Fs and green vegetation proxies. Left: Cornfield mean values. Cornfield standard deviations are displayed as error bars. Right: Relationship for all pixel values within a profile. Individual cornfields are distinguished by different symbols.

Both suggest that Fs is highly coupled to the amount of green vegetation as estimated by the proxies for green vegetation. This is allegeable since an increase in canopy greenness implies an increase in green leaves or, respectively, photosynthetic pigments absorbing photosynthetically active radiation. This, in turn, increases the amount of emitted Fs. The type of relationship seems to be related to the sensitivity of the vegetation proxies to increasing canopy density. The NDVI is known to enter a saturation phase over densely vegetated surfaces (Liang, 2004). As a result, Fs increases exponentially with increasing NDVI and, therefore, provides a higher differentiation of values than the NDVI. By contrast, the SR and the FCC seem to be less susceptible to high canopy densities. This causes both variables to further increase with increasing Fs, which is resulting in a rather linear relationship. However, for very high SR and FCC values (MC4) slight deviations from the common linear trend can be found. This might be an indicator for both parameters loosing their sensitivity to increasing canopy density whereas the Fs emission still increases.

Nonetheless, there is also evidence of differences between Fs and proxies for green vegetation. First, a high dispersion of values can be observed in the scatterplots of all profile values. This indicates the high variation of Fs with increasing amount of green vegetation. Second, when only considering individual cornfields, no relationship between Fs and the corresponding vegetation proxy can be observed. Coefficients of determination are lower than 0.48 (Table 1) and no clear trends can be found when comparing the cornfield standard deviations of Fs with corresponding standard deviations of the vegetation proxies. And third, as already mentioned, the intra-field Fs variability is clearly higher than the intra-field variation of the SR, NDVI and FCC. All these observations point to the surplus value of Fs compared to proxies for green vegetation.

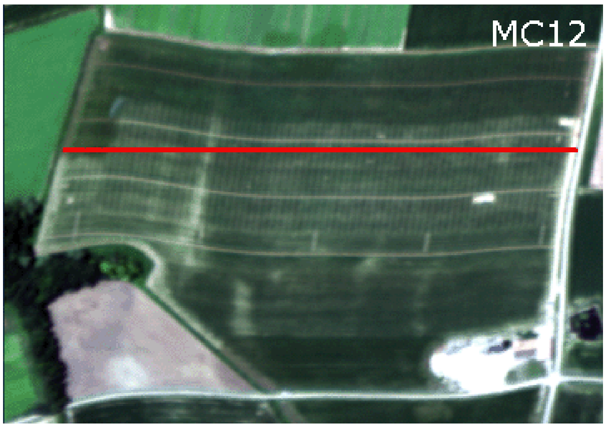

Figure 4: Transect through a highly heterogeneous (MC12) and a rather homogeneous (MC4) cornfield to illustrate the effect of the canopy structure on the variability of Fs. Refer to Figure 2 for the corresponding along-track profiles.

The influence of canopy structural effects on the Fs signal are yet not well known, however, may play an important role in explaining part of the observed variability (Rascher et al., 2009). In general, several structural variables are used to characterize the canopy architecture. The effect of canopy density, as estimated by the vegetation proxies, was already discussed above. However, other structural components of a plant canopy, e.g. sunlit surface, plant shadow or the background soil, might play an important role when interpreting the variability of the Fs signal. In order to give an insight in how the canopy architecture might account for the variability of Fs, two from the structural point of view different cornfields are addressed in the following (Figure 4). MC4 is a cornfield with a fairly homogeneous dense canopy. Corn rows are planted very close to each other and plants are on average higher than 2 m. Results from the spectral mixture analysis indicate almost 100% corn fraction throughout the field. The influence of the soil background is only limited to the field boundary. By contrast, MC12 is a highly heterogeneous cornfield with a rather open canopy. Clear structures can be observed within the field, which is due to the low plant height (1.2 m on average) and due to missing corn rows. As a result, the FCC is rather low (not greater than 70%) and the influence of the soil background in the canopy is high (greater than 20%). Differences in the level of canopy fluorescence between both fields can be attributed to differences in the amount of green vegetation. However, when comparing the intra-field variability of Fs, it becomes obvious that the variation of the signal in MC12 is clearly higher than the variability of the signal in MC4. From this it follows that external factors, such as shadow effects or scattering interactions with the background components, might have an essential influence on the canopy Fs signal. This applies particularly when remotely sensing rather spares canopies, where the observed ground is not fully covered with leaves. Consequently, although only descriptively illustrated, it must be assumed that at least a part of the observed differences in the intra-field variability of the Fs signals can be explained by differences in the structural properties of the corn canopy.

4. CONCLUSIONS

Due to a variety of disturbing effects, deriving sun-induced chlorophyll fluorescence by means of airborne hyperspectral data turned out to be challenging. Data analyses were limited to along-track profiles represented by single image columns with constant view and illumination geometry. In doing so, it was possible to provide information on the spatial variability of Fs beyond standard point observations.

The comparisons between Fs and three different green vegetation proxies, SR, NDVI and FCC, have contributed to a more profound understanding of the derived fluorescence signal. Results of our research prove that the level of Fs is controlled by the amount of green vegetation and that non-linearities between Fs and NDVI are not sufficient to explain differences in fluorescence emission. These are most likely caused by the insensitivity of the NDVI to increasing canopy density, for which SR and FCC are less susceptible. With regard to this, however, it must be kept in mind that the findings are based on a limited number of cornfields. Inter-species differences might exist, but have not been investigated. Nevertheless, two major aspects point to differences in the information of the sun-induced fluorescence signal and the proxies for green vegetation. First, Fs exhibits a much higher intra-field variability, and second, Fs shows no dependency with the vegetation proxies when limiting the range of observation (e.g. within individual fields). Both aspects suggest that the exclusive use of field mean values, where more than 90% of the variance in Fs could be explained by the SR or the FCC using a linear function, might not be enough to explain Fs variability.

However, several unexplained aspects have to be considered when evaluating the variability of the derived fluorescence signal. These include the influence of canopy structural effects, the influence of random sensor noise and introduced trends in vegetation reflectance. This remains uncertain within the presented results and needs more detailed upscaling experiments to quantify related impacts on Fs in the future.

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