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BACKGROUND Chlorophyll fluorescence offers strong potential to assess plant photosynthesis over large areas using Earth observation technology. To implement reliable remote sensing approach for estimation of plant photosynthesis, research efforts are needed evaluating the associated diurnal and seasonal dynamics in environmental conditions and vegetation properties.

GOALS The goals of this study are to assess the dynamic diurnal and seasonal relationships between vegetation photosynthetic function and its spectral fluorescence and reflectance properties, at both leaf and canopy scales.

METHODS During the summer growing seasons of 2014–2016 we collected complimentary leaf and canopy measurements of corn (*Zea mays*, L.), growing under a range of nitrogen levels, ranging from deficiency to excess. Leaf measurements included: photosynthetic pigments, chemical constituents, incident PAR, optical properties, photosynthesis (Amax) and the associated emitted fluorescence parameters (e.g. Fs, Fmax', NPQ, ETR, etc.; LI6400, LI-COR Biotech., Lincoln, NE, US). Leaf fluorescence parameters were measured with LI6400 and a monitoring PAM fluorimeter (MONI-PAM; Walz, Germany). Canopy measurements included CO₂ flux assimilation from eddy covariance flux tower; and reflectance and red and far-red solar induced fluorescence (SIF) collected with: the GSFC FUSION automated system, and an experimental Piccolo system (optimized for deriving SIF in 2016). The specifications of the FUSION and Piccolo systems are available at [ftp://fusionftp.gsfc.nasa.gov/FUSION/](http://fusionftp.gsfc.nasa.gov/FUSION/) and <http://www.congrexprojects.com/2014-events/14c04/proceedings>, respectively. Using the GSFC automated FUSION system we measured diurnal changes in canopy reflectance and SIF throughout the growing season for corn growing in optimal nitrogen treatment (N 100%). In 2016 we tested a new SIF-optimized Piccolo (MacArthur et al. 2014) system.

PROCESSING Fluorescence (SIF) was calculated from both systems (FUSION and Piccolo) applying the 3 FLD approach, as a depth ratio between spectral features from the reference panel and the vegetation, at the atmospheric absorption features centered at 688nm and 760nm. Their ratio SIF_{red/far-red} was also calculated. The normalized difference vegetation index (NDVI) was calculated from FUSION reflectance as a normalized reflectance ratio using 800 and 670 nm wavelengths (Table 1). The photochemical reflectance index (PRI) was calculated from reflectance as a normalized reflectance ratio using 531 and 570 nm wavelengths. We analyzed leaf and canopy data from days representative of the corn growth stages: vegetative young and mature, reproductive tussling, and senescent. The FUSION data was collected in 2014 on July 30, August 7 and September 26. Leaf and canopy optical measurements were compared with Amax, GEP and Light Use Efficiency (ϵ) derived from flux data, $\epsilon = \text{GEP}/(\text{FAPAR} * \text{Qin}) = \text{GEP}/\text{Qa}$, where GEP is gross ecosystem productivity, Qin is incident Photosynthetically Active Radiation (PAR), FAPAR is the fraction of absorbed PAR estimated from NDVI, and Qa is the absorbed PAR.

RESULTS

Leaf level corresponding changes in photosynthesis and fluorescence emissions

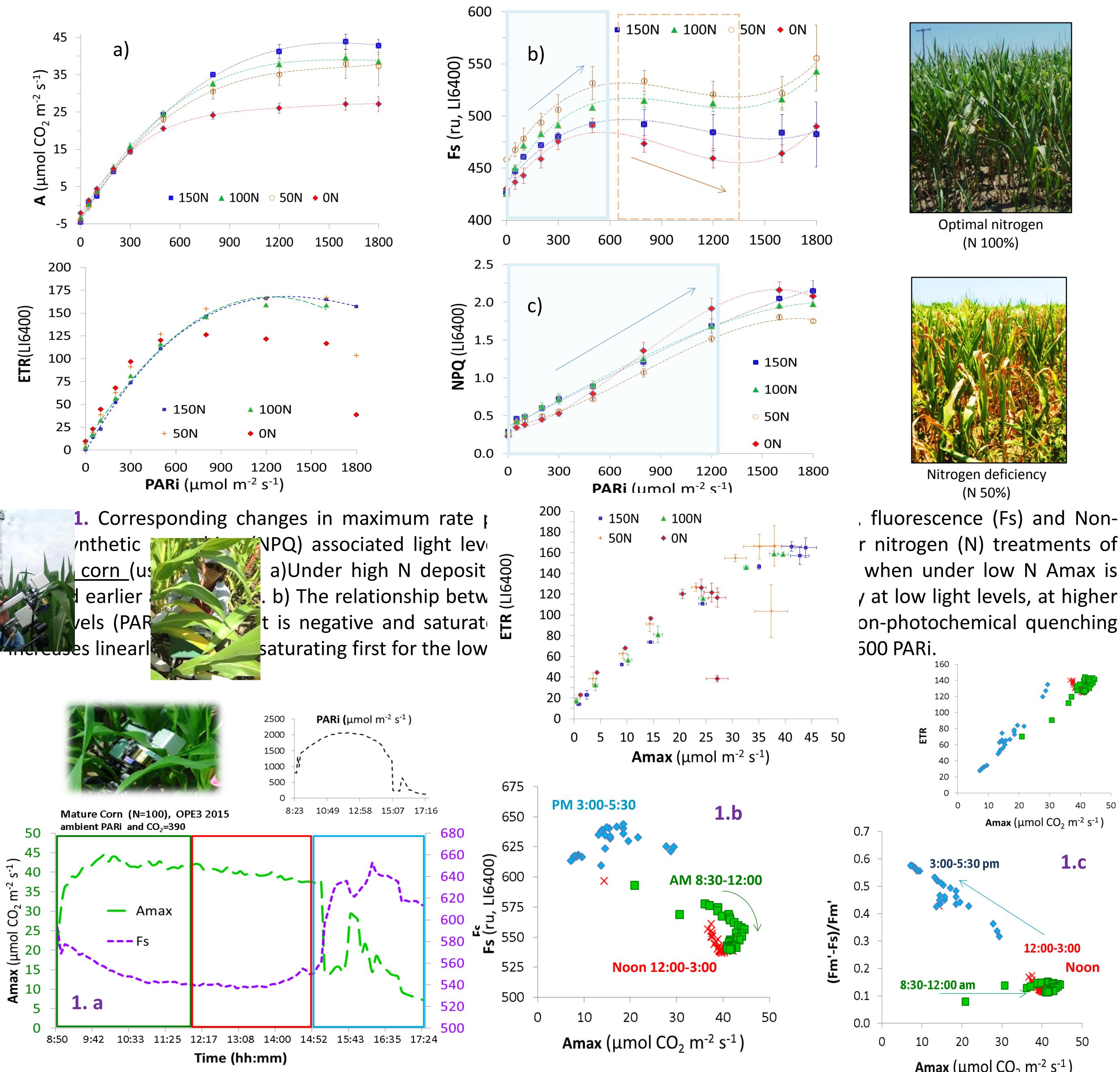


Figure 2. For mature corn under optimal nitrogen treatment, the corresponding diurnal changes in photosynthesis (Amax) and steady state fluorescence (Fs) are exhibiting a pattern of hysteresis (a, b, and c - measured with LI6400).

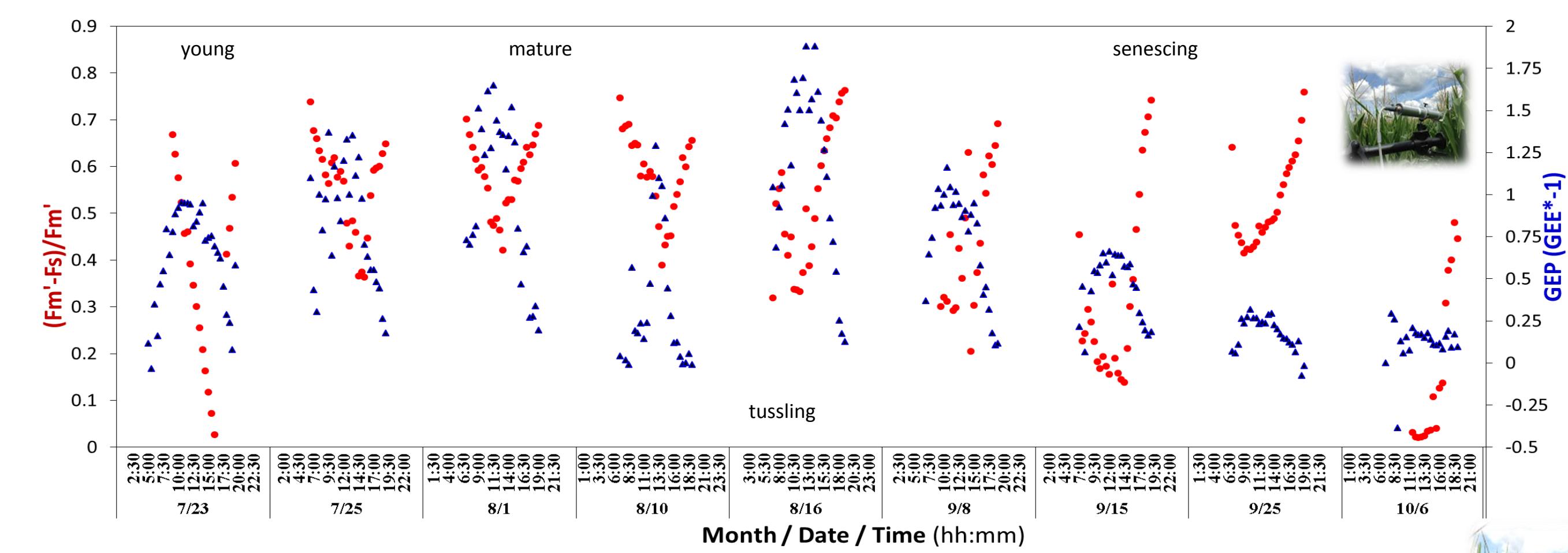


Figure 3. Diurnal and seasonal changes leaf differential fluorescence DF=(Fm'-Fs)/Fm' (BLUE, MONI-PAM, $\mu\text{mol m}^{-2} \text{s}^{-1}$) and GEP (RED, $\text{mg m}^{-2} \text{s}^{-1}$), measured on corn under optimal nitrogen deposition (N=100%, OPE3 2015).

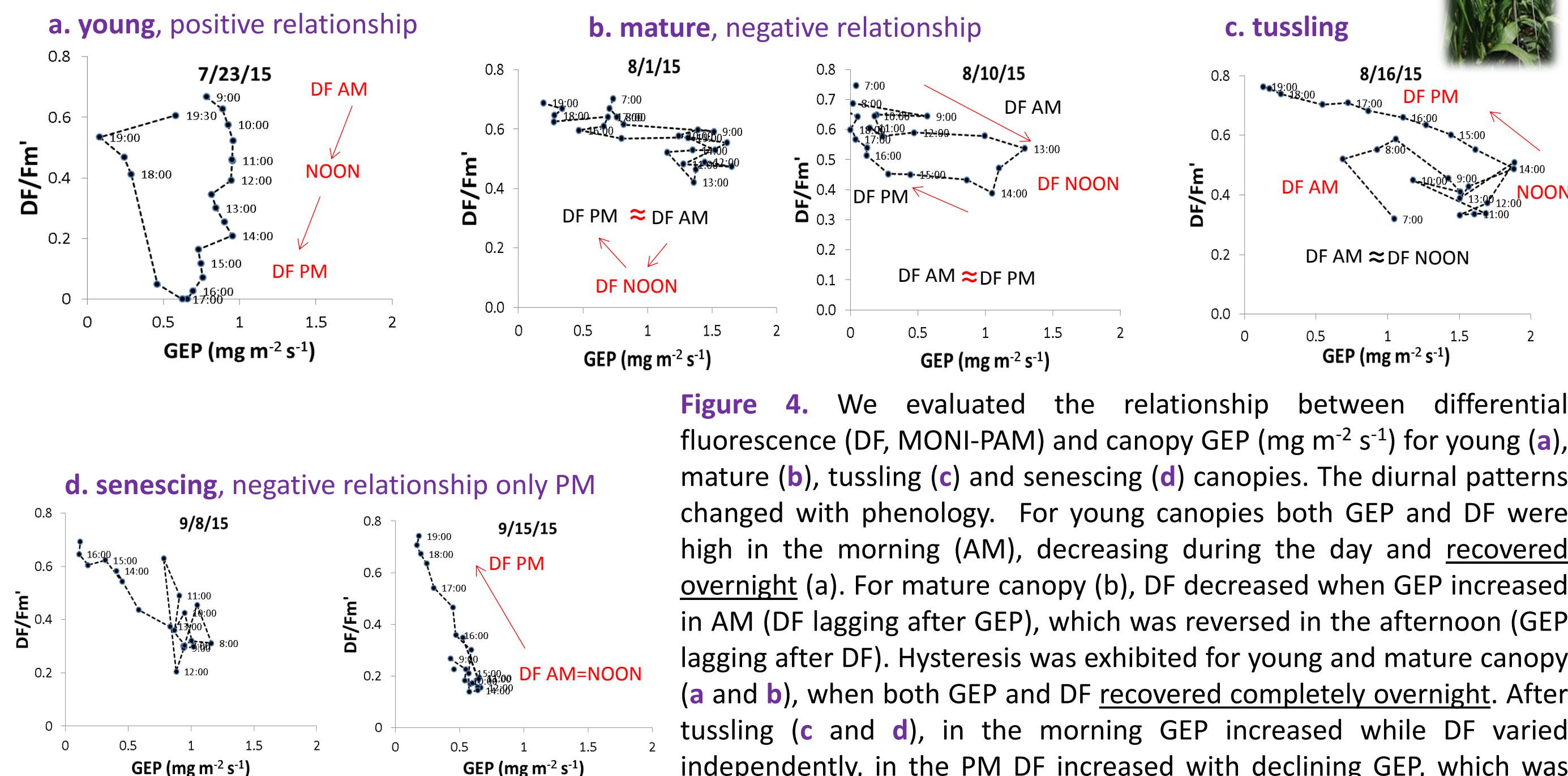


Figure 4. We evaluated the relationship between differential fluorescence (DF, MONI-PAM) and canopy GEP ($\text{mg m}^{-2} \text{s}^{-1}$) for young (a), mature (b), tussling (c) and senescing (d) canopies. The diurnal patterns changed with phenology. For young canopies both GEP and DF were high in the morning (AM), decreasing during the day and recovered overnight (a). For mature canopy (b), DF decreased when GEP increased in AM (DF lagging after GEP), which was reversed in the afternoon (GEP lagging after DF). Hysteresis was exhibited for young and mature canopy (a and b), when both GEP and DF recovered completely overnight. After tussling (c and d), in the morning GEP increased while DF varied independently, in the PM DF increased with declining GEP, which was more pronounced during senescence (d).



Canopy changes in SIF Red and Far-Red emissions

FUSION produces seasonal and diurnal profiles of spatially resolved, high spectral resolution calibrated VNIR radiance ($\text{W m}^{-2} \text{nm}^{-1} \text{sr}^{-1}$) measurements, which are ideal for the study of vegetation function in relation to its reflectance and SIF bi-directional properties.

Table 1. FUSION SIF_{red} (SIF 685), SIF_{far-red} (SIF 760), ratio SIF_{red/far-red}, PRI (NPQ) and NDVI means and coefficient of variation (CV=SD/mean).

FUSION	8/4/2014		8/15/2014		9/23/2014	
	AM	PM	AM	PM	AM	PM
Mean						
SIF 685	0.00042	0.00045	0.00034	0.00037	0.00039	0.00033
SIF 760	0.0012	0.0016	0.0015	0.0017	0.0007	0.0009
SIF R/FR	0.35	0.27	0.23	0.20	0.58	0.38
PRI	0.017	0.011	-0.004	-0.009	-0.057	-0.052
NDVI	0.92	0.90	0.92	0.92	0.86	0.86
Coefficient of Variation (CV = STDeviation/Mean)						
SIF 685	0.44	0.34	0.41	0.43	0.32	0.39
SIF 760	0.23	0.21	0.29	0.29	0.33	0.26
SIF R/FR	0.32	0.18	0.30	0.32	0.45	0.23
PRI	0.65	0.43	-1.81	-0.68	-0.32	-0.15
NDVI	0.03	0.04	0.03	0.02	0.06	0.04



We observed diurnal and seasonal changes in both SIF685 and SIF760 (Tab. 1, Fig. 5). SIF685 was always lower as compared SIF 760. Both SIF685 and SIF760 declined during the season (Fig. 5 a). The CV for both SIF parameters was higher in the morning (as compared to PM) and increased throughout the season (Tab. 1). The SIF688/760 ratio decreased during the season (Fig. 5 b), indicating a change in the proportion of SIFred and SIFfar-red emissions.

Changes in PRI were clearly seen throughout the day. We measured higher PRI in the mornings, which was more pronounced earlier in the season (August 4th). During the season PRI declined from 0.04 (August 4 - maximum) to -0.05 (September 23 - minimum). With the advancement of senescence, the PRI variation declined (see CV for PRI, Tab. 1). Comparing morning to afternoon NDVI we did not observe significant differences. From August 4, 2014 to September 23, 2014 NDVI declined from 0.92 to 0.86 (Tab. 1).

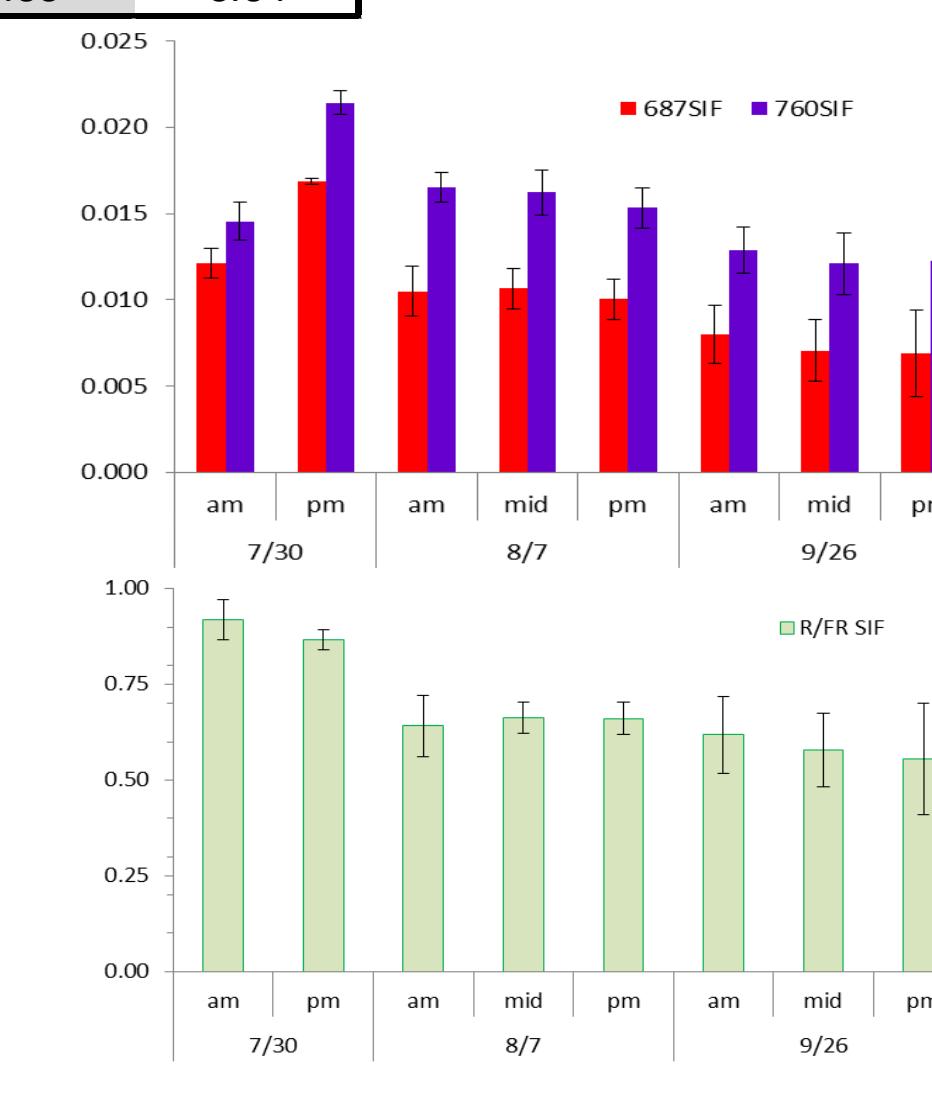


Figure 5. Diurnal and seasonal differences in FUSION SIF685 and SIF760 (a) and their ratio (b).

Canopy comparison of gross ecosystem production (GEP) and FUSION fluorescence (SIF760)

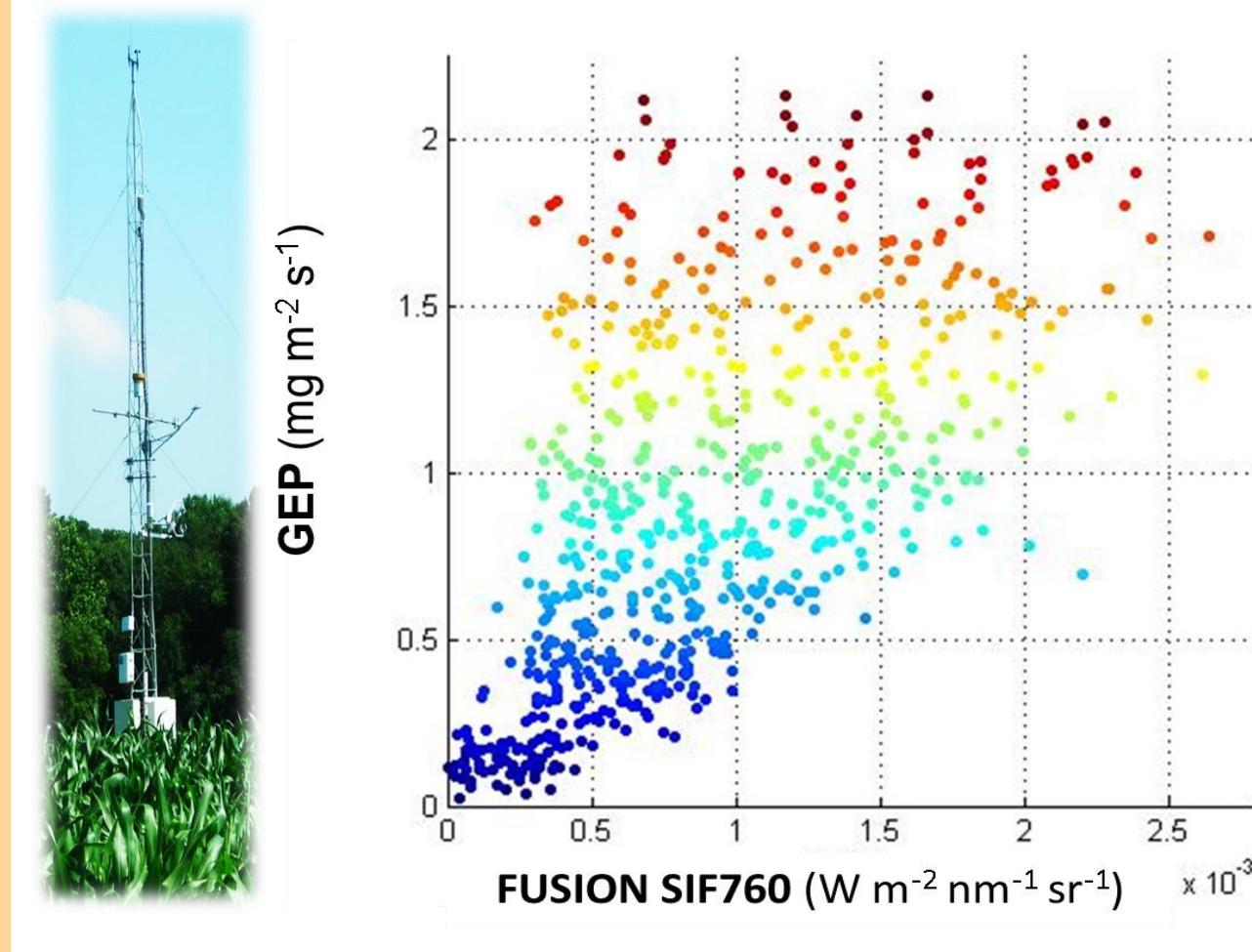


Figure 6. Comparison of GEP and FUSION SIF760 (VZA25°, VAA330°). The comparison includes 632 measurements, collected from 8/1 to 10/15, 2014. Included are half-hourly observations when SZA < 60°.

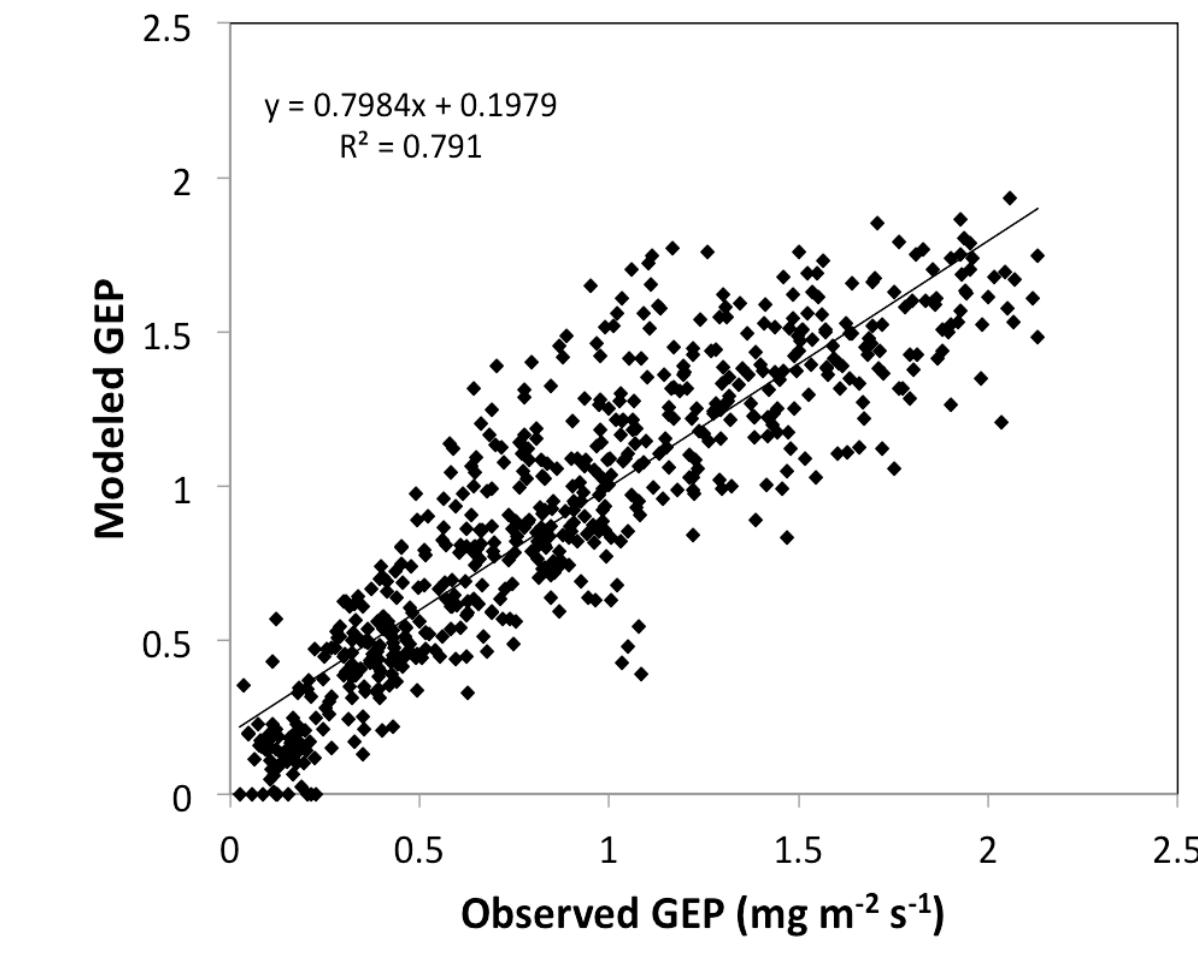


Figure 7. Observed GPP vs. FUSION modeled. The FUSION model of GEP combines use of NDVI, PRI, SIF760, and Incident PAR.

Next-Generation Spectral Systems for diurnal and seasonal measurements

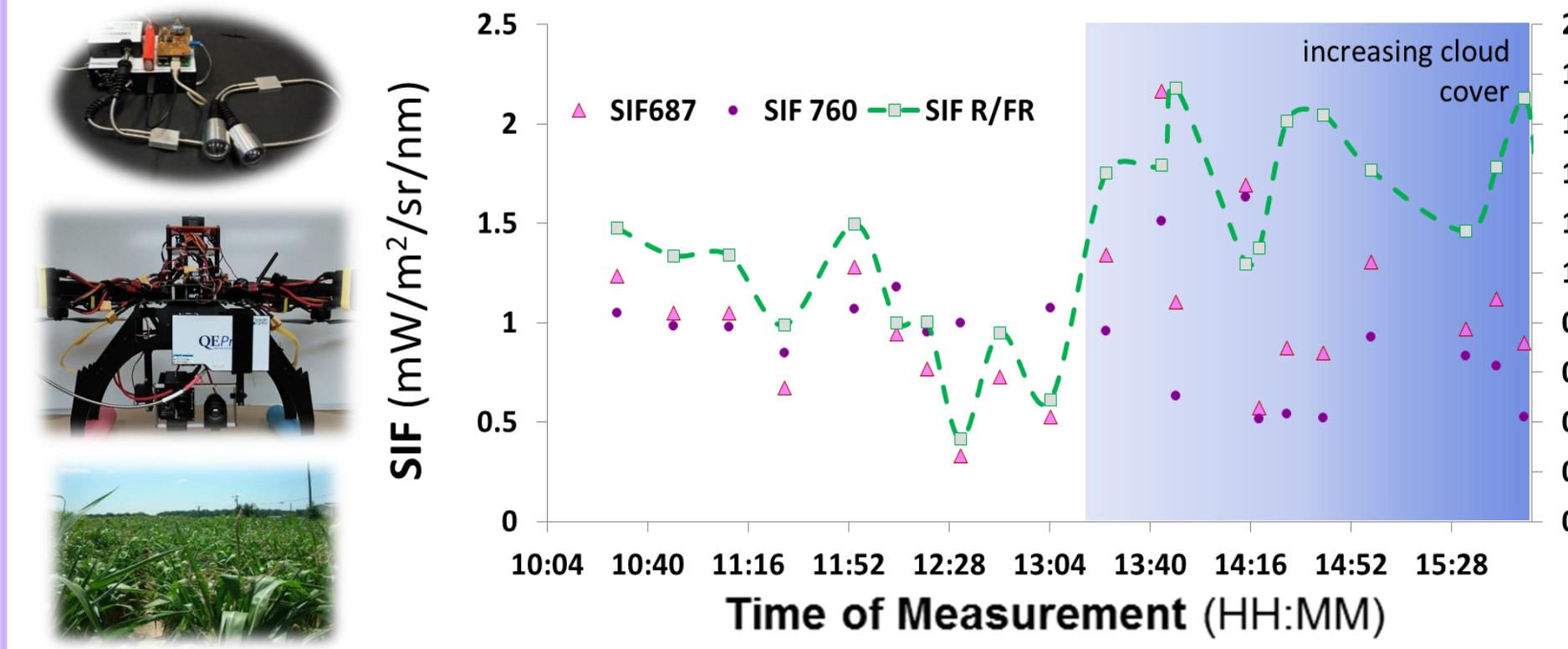


Figure 8. An automated Piccolo system, optimized for SIF retrieval was able to measure both SIF_{red} and SIF_{far-red} under varying cloud conditions, when other SIF systems can not. The SIF_{red/far-red} ratio increased in the afternoon under increasing cloud conditions. The Piccolo system measured diurnal canopy SIF and produced results comparable to leaf, canopy, air- and space-borne systems.

TAKE-HOME MESSAGE

- Photosynthesis and chlorophyll fluorescence are positively related only at low light levels, when the rate of photosynthesis is low. At higher light levels ($700-1200 \text{ PAR}_i, \mu\text{mol m}^{-2} \text{s}^{-1}$), when the rate of photosynthesis is optimal the relationship with chlorophyll fluorescence is negative. At high light photosynthesis saturates (the Amax/Fs relationships decouples), which is reached earlier for low N level.
- Non-photochemical quenching increases linearly with increasing light until saturation ($\text{PAR}_i \approx 1300$).
- Differential Fluorescence (DF, MONI-PAM) and GEP from flux tower were closely associated. Their relationship was positive only for young canopy, it was negative for mature and senescing canopy, exhibiting a pattern of hysteresis for the mature canopy.
- FUSION diurnal and seasonal SIF760 were strongly related to GEP and Light Use Efficiency (ϵ) derived from flux tower measurements. Canopy diurnal and seasonal trends in FUSION PRI, SIF685, SIF760 and SIF685/760 provided complimentary information. Using these FUSION parameters, in combination with PARi, we obtained FUSION GEP estimates, strongly related to GEP ($R^2=0.79$) measured by the eddy covariance tower.
- New Generation (NG) spectral systems with automated optimization are needed to capture the diurnal and seasonal dynamics in vegetation function under varying PARi sun/cloud levels. Calibrated spectroscopy data is required at all temporal and spatial scales, to bridge the gap between *in-situ* leaf, proximal, air- and space-borne observations.

FUTURE Directions

- Currently, SIF leaf and canopy are measured under high sun-light ($\text{PAR}_i > 700 \mu\text{mol m}^{-2} \text{s}^{-1}$) when the SIF signal is sufficient to yield SIF_{red} and SIF_{far-red}. Satellites measure SIF under low light when photosynthetic rate is not optimal, yielding SIF_{far-red}. Photosynthetic function is drastically different under low and high light. To scale from *in-situ*, to canopy, air- and future space-borne measurements (e.g. ESA/FLEX) we are implementing an automated spectral system, measuring reflectance and SIF under both high and low light levels.
- As a next step, we will combine the leaf and canopy measurements within the SCOPE modeling approach to investigate the dependence between leaf and canopy level photosynthetic estimates, and the associated reflectance and fluorescence properties, as they change diurnally and with phenology, under varying environmental factors.

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