Editorial Special Issue:
Advancing Foundational Sun-induced Chlorophyll Fluorescence Science

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The first research on the possibilities offered by chlorophyll-*a* fluorescence to track the daily course of CO_2 assimilation by leaves dates back to the last century (Kautsky and Hirsch, 1931). In the second half of the XXth Century, the development of the field of active fluorescence, which relies mainly on the pulse amplitude modulation (PAM) fluorimetry technique, allowed unraveling the relationship between the yield of chlorophyll-a fluorescence and that of photochemistry (linear electron transport), which is modulated by a third process known as non-photochemical quenching (Genty et al., 1989). Since then, active fluorescence has been regularly used in ecophysiology, forestry, and crop sciences to understand the plant response to stress (Schreiber, 2004).

Since the beginning of the 2000ths, the development of portable field spectrometers allows for measuring passive sun-induced fluorescence (SIF) at strong solar or telluric absorption features, which do not rely on the use of artificial excitation light (e.g., Meroni and Colombo, 2006; Meroni et al., 2009; Perez-Priego et al., 2005). Since then, the field has rapidly evolved, and now fluorescence is measurable with automated field spectrometers in the field (Grossmann et al., 2018; Gu et al., 2019b; Rossini et al., 2010), airborne platforms (Rascher et al., 2015; Zarco-Tejada et al., 2000), and satellites (Guanter et al., 2012; Sun et al., 2018). These advances offer the potential to couple ecosystem-scale measurements of CO_2 fluxes and SIF to probe new aspects related to ecosystem structural impacts on SIF and photosynthesis processes at different time-scales and on different ecosystems (e.g., Damm et al., 2010; Magney et al., 2019; Porcar-Castell et al., 2021). While SIF has been proven as a good proxy of gross primary productivity (GPP), mainly across large spatial and temporal gradients, a series of studies showed that different factors could confound this relationship, namely different canopy structures (e.g., Dechant et al., 2020; Migliavacca et al., 2017), stress conditions (e.g., Martini et al., 2022; Wieneke et al., 2018; Wohlfahrt et al., 2018), nutritional conditions (Cendrero-Mateo et al., 2015; Martini et al., 2019), species-specific differences (e.g., Van Wittenberghe et al., 2013) and light regimes (e.g., Liu and Liu, 2018). At the same time, the modeling of SIF developed rapidly (Gu et al., 2019a; Han et al., 2022; Han et al., 2021; van der Tol et al., 2014; van der Tol et al., 2009) and with an increasing degree of realism, offering the possibility to retrieve important vegetation parameters from remote sensing (Pacheco-Labrador et al., 2019; Verrelst et al., 2015; Verrelst et al., 2016; Zhang et al., 2014). Excellent and comprehensive reviews of the field are by (Mohammed et al., 2019; Porcar-Castell et al., 2021; Porcar-Castell et al., 2014; Sun et al., 2023a; Sun et al., 2023b).

Despite the exponential increase in the number of publications in the field, significant progress is still needed. This special issue aims to report foundational SIF science, including theoretical modeling and measurement-based research that is urgently needed to unleash the full potential of SIF for physiological and ecological applications at scales spanning from leaf to globe. The 14 articles collected in this special issue reported on the following specific aspects:

first, technical capabilities enabling spectrally resolved SIF observations and their inter-comparability in space and time; **second**, theoretical developments in SIF-photosynthesis relationships to correctly interpret the signal and extract mechanistic information on vegetation structure and function; **third**, evaluation of the potential of SIF to track process beyond photosynthesis, such as transpiration; **fourth**, large scale-applications of SIF observations; and **finally**, upscaling fluorescence from leaf to canopy scales.
Below we report a summary of the articles presented in the special issue divided by thematic areas:

- ***Technical capabilities enabling spectrally resolved SIF observations and their inter-comparability across space and time*.** Due to the presence of solar radiance within the wavelength range of fluorescence emission, SIF cannot be observed directly. Rather it must be inferred from the matched incoming and outgoing radiance measurements at some deep absorption spectral features using sophisticated retrieval methods. It remains undetermined what the best method is for this purpose. **Naethe et al., (2022)** developed a new method based on the Partial Least Squares (PLS) regression machine learning to retrieve red and far-red SIF from up-welling radiance spectra. They found that the PLS method does not require complex, error-prone atmospheric corrections, and thus allows faster and more robust inference of SIF. Besides retrieval methods, different observing platforms may introduce different complexities in SIF observation. **Wang et al., (2022)** compared a UAV- and an airborne-based system in their far-red SIF measurements over structurally different crops. Consistent temporal and spatial patterns in SIF emission were obtained with both systems over most crop types. This agreement encourages applications of both platforms in agriculture. **Cheng et al., (2022)** developed a harmonization strategy to allow SIF acquired at different times of a day to be scaled up to daily averages for comparisons across different satellite platforms which varied in overpass times. Their approach explicitly considered the atmospheric extinction of solar radiation and topographical effects.
- ***Complexities in SIF-photosynthesis relationships*.** Theory predicts complex, non-universal SIF-photosynthesis relationships (Gu et al., 2019a; Sun et al., 2023a). Consistent with these theoretical predictions, **Wieneke et al., (2022)** demonstrated that the

relationship between fluorescence and photochemical quantum efficiencies was non-monotonic across a phosphorus limitation gradient and it was not feasible to predict one from the other alone. **Yang et al., (2022)** characterized the responses of red SIF and GPP to variations in environmental drivers across seasons in a high-elevation coniferous forest. They found that red SIF and GPP did not always vary in synchrony. Such asynchronous variations were likely due to the activation/deactivation of photosystems out of sync with the timing of water availability for photosynthesis**.** Generally, red SIF is thought to be more strongly affected by canopy re-absorption, which reduces the physiological information in the signal. **Burareal et al.** show for a rice canopy during the mid to late growing period that red SIF correlates at least as good, if not better, with GPP than far-red SIF. The herbicide experiment conducted by **Wu et al., (2022)** emphasized the message that SIF-photosynthesis relationships are complex. These authors applied herbicides to a maize field with weeds. While the maize was herbicide-resistant, the weeds were not. After the herbicide treatment, SIF increased, but the eddy covariance-derived GPP decreased, demonstrating physiological stress could result in a decoupling between SIF and GPP. **Liu et al., (2021)** used a modeling approach to demonstrate that simple correlational analyses may introduce uncertainties to SIF-GPP relationships if the dynamics in the ratio of light use efficiency to fluorescence quantum yield were not explicitly considered. A further complication in the SIF-photosynthesis relationships is the angular effects in the diurnal variations of SIF, as demonstrated by **Zhang et al., (2020)**. Their measurements over crop canopies revealed a strong dependence of top of canopy red and far-red SIF on viewing angles.

- ***Evaluation of the potential of SIF to track processes beyond photosynthesis*****.** Two studies demonstrated that SIF can be used to study broader ecosystem processes. **Damm et al., (2021)** combined field observation and modeling to demonstrate the potential of SIF to characterize transpiration in a well-watered mixed forest. By exploiting the fact that photosynthetic CO_2 uptake and transpiration are determined by stomatal resistance, they suggest a novel SIF-based transpiration assessment approach. **Zhou et al., (2022)** integrated SIF and meteorological variables with Fick's law and an optimal stomatal behavior model to estimate evapotranspiration. They validated their novel approach against eddy covariance flux measurements and found better performance over traditional methods. These studies encourage SIF researchers to broaden the applications of SIF to other areas (also see Sun et al. 2023b).
- ***Large scale-applications of SIF observations*****.** Two studies continued the popular line of SIF investigation at a large scale. **Bai et al., (2022)** investigated the causes of the variability of the GPP-SIF relationship using different satellite SIF datasets, i.e., downscaled fine resolution SIF from the Orbiting Carbon Observatory-2 (GOSIF) and Global Ozone Monitoring Experiment-2 SIF (downscaled GOME-2 SIF). The authors concluded that the spatiotemporal variations of GPP-SIF relationship could improve the GPP simulation, in particular, the simulation of peak GPP values. **Qiu et al., (2022)**

compared different satellite products in their application to monitor drought impacts on crop productivity in the US Midwest. They found that with its high spatial resolution, GOSIF outperformed GOME-2 SIF and MODIS Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and the near-infrared reflectance of vegetation (NIRv) in this application.

- ***Upscaling fluorescence from leaf to canopy scales*****.** The upscaling of fluorescence from leaf to canopy scales is more complex than solar radiative transfer, even though the physics remains the same because the sources of fluorescence emission are spatially distributed inside the canopy. **Cui et al., (2020)** modeled fluorescence radiative transfer inside plant canopies. They particularly separated sunlit and shaded leaves. Their approach was efficient enough to be applied at regional and global scales.

Although the articles collected in this special issue cover a broad range of topics in SIF science, they represent only a small fraction of the rapidly growing SIF literature. However, as demonstrated in this special issue and also summarized in Sun et al. (2023a and b), many challenges remain. We hope this special issue will encourage a new generation of SIF researchers to continue tackling these challenges.

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