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Potential of solar-induced chlorophyll fluorescence to estimate transpiration in a temperate forest

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A B S T R A C T

By utilizing continuous measurements of water fluxes and solar-induced chlorophyll fluorescence (SIF) over the entire growing season, we exploit the potential of broadband SIF in predicting plant transpiration (*T*) in a temperate forest. After reconstructing the full SIF spectrum from the selected absorption lines and simulations from the SCOPE (Soil Canopy Observation Photochemistry and Energy fluxes) model, linear regression (LR) and Gaussian processes regression (GPR) models are used to analyze the relation between *T* and combinations of different SIF bands. We find that SIF emissions in the near-infrared spectrum (at 720 nm, 740 nm and 760 nm) are more sensitive to *T* than SIF emissions in the red spectrum (at 685 nm and 687 nm). While conditions such as light and heat stress decouple the relationship between single-band SIF and *T*, the combination of different SIF bands allows the retrieval of reliable *T* estimates even in these conditions. Overall, we find that the use of SIF as a proxy for *T* yields estimates that are at least as accurate as those from traditional transpiration models such as the Penman-Monteith equation, which are input demanding and complex to apply to *in situ* and satellite data. Specifically, we find that (1) the SIF-*T* relationship deteriorates when Photosynthetically Active Radiation (PAR), vapor pressure deficit and air temperature exceed biological optimal thresholds; (2) a high leaf area index exerts a negative impact on the SIF-*T* correlation due to increasing scattering and (re)absorption of the SIF signal; (3) the SIF-*T* relationship does not change depending on the observation time during the day; and (4) temporal aggregation to days further enhanced the SIF-*T* correlations. Altogether, our results provide the first ground-based evidence that SIF emission has potential to be a close predictor of plant transpiration, especially when a combination of different SIF bands is considered.

1. Introduction

In terrestrial ecosystems, most of the Absorbed Photosynthetically Active Radiation (APAR) is consumed by plants in photosynthetic activities and non-photochemical quenching (NPQ) processes. The rest is reemitted by chlorophyll (Chl) molecules at a longer wavelength, resulting in a subtle glow of energy in the visible and near-visible part of the spectrum that is commonly referred to as solar-induced chlorophyll fluorescence (SIF). Although amplitude of SIF varies in the range of 640–850 nm depending on plant physiological conditions, environmental stress, and canopy structure, plants in general show two peaks in SIF emission: one in the red spectral region (640–700 nm), with a maximum near 685 nm (SIF_{red}), and the other in the near infrared region, with a peak around 740 nm (SIF_{NIR}). These different SIF spectral regions contain valuable signals on the photosynthetic process and its responses to environmental conditions (Franck et al., 2002). For example, SIF_{red} is more related to the photosystem II (PSII), while large part of SIF emission in the near-infrared region (SIF_{NIR}) comes from the contribution of both photosystem I (Psi) and PSII (Baker, 2008; Papageorgiou & Govindjee, 2004). The dynamics of SIF are mainly driven by PSII photochemistry because the contribution of fluorescence from Psi is generally weak and remains constant, thus SIF_{red} is expected to hold a stronger correlation with photosynthesis (Genty et al., 1990; Palombi et al., 2011).

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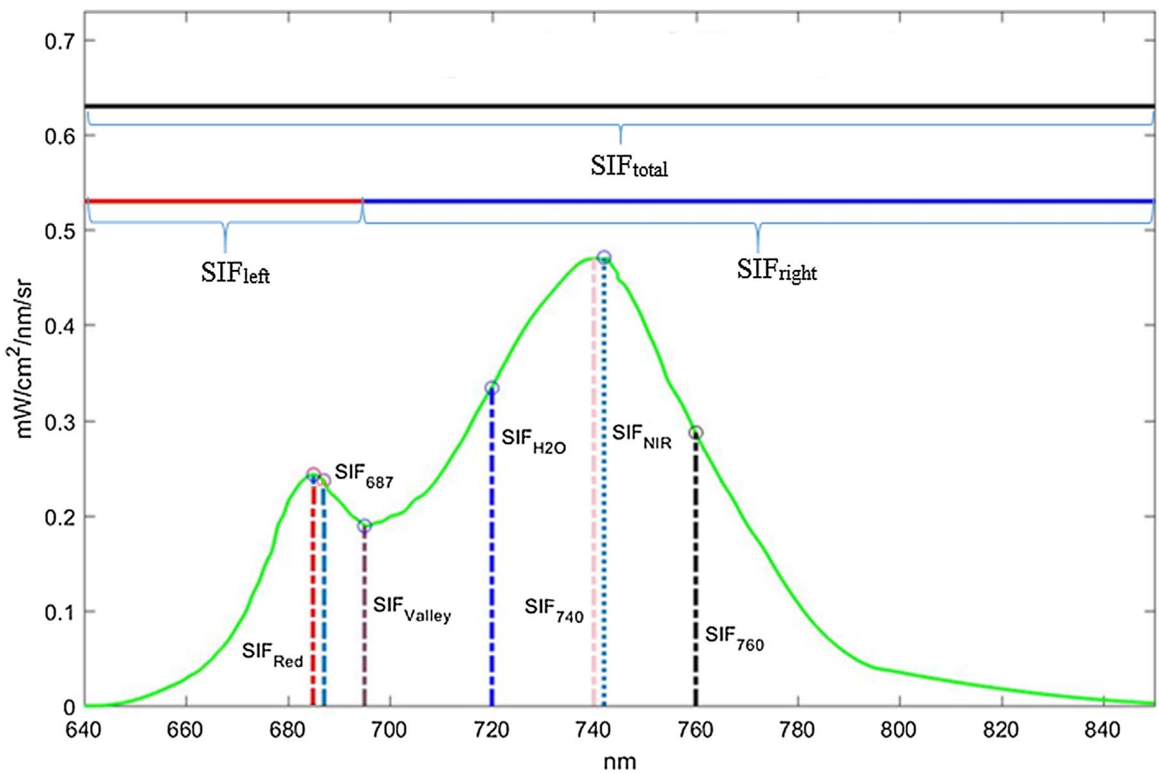

Fig. 1. The locations of the selected SIF spectral features including the SIF emission in the O_2-B (SIF_{687}), H_2O (SIF_{720}) and O_2-A (SIF_{760}) absorption lines, the three spectral integration ($SIF_{left,}$ SIF_{right} and SIF_{total}), the two SIF emission peaks in the red (SIF_{red}) and near infrared (SIF_{NIR}) region and the valley (SIF_{Valley}) between them in a reconstructed SIF spectrum. Note that shapes of SIF spectrum vary in response to environment conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

However, most of recent studies exploited only one SIF band, mostly in the 730–770 nm window, largely because of the strong absorption line by O2 in the atmosphere (The O_2-A band) making it relatively easy to record. Because of the reabsorption of the fluorescence within the canopy, SIF emitted in the red region has seldom been exploited (Joiner et al., 2016). SIF emission at 760 nm has been shown to be correlated with gross primary productivity (GPP) in both forest and crop ecosystems (Damm et al., 2010, 2015; Guanter et al., 2014; Zhang et al., 2014; Guan et al., 2016; Yang et al., 2015 ; Yang et al., 2017), and SIF at 740 nm has been shown to be sensitive to plant water stress (Perez-Priego et al., 2005; Lee et al., 2013) and herbicide application (Rossini et al., 2015). Only recently, model-based studies investigated the relationship between full SIF emission and different environmental factors (Verrelst et al., 2016; Zhang et al., 2016), showing that SIF bands have different sensitivities to biochemistry and leaf/canopy variables, and that a combination of these bands could yield a closer diagnostic of plant photosynthetic activity (Zhang et al., 2016).

Although the global terrestrial water cycle is dominated by transpiration (*T*) (Jasechko et al., 2013), *T* remains one of the most uncertain and elusive hydrological variables at global scale (Dolman et al., 2014). This is due to the impossibility to measure this flux directly from space and the scarcity of global *in situ* measurements (Fisher et al., 2017). Most eddy covariance-based water flux studies combine *T* and evaporation into evapotranspiration (ET), an aggregated process of physical and biological processes, obscuring environmental controls on *T* (Tang et al., 2006). For example, the influence of stomatal conductance on the simultaneous uptake of CO_2 for photosynthesis and release of vapor through transpiration couples the terrestrial carbon and water cycles, thus variations in *T* are expected to closely relate to the photosynthetic machinery (Sellers et al., 1985; Jarvis and Davies, 1998) and possibly SIF, while evaporation from soils does not contain such direct link. In fact, several studies based on satellite-derived SIF datasets have already shown significant declines in both SIF and *T* during severe drought events (Lee et al., 2013; Sun et al., 2015; Yoshida et al., 2015). Because SIF can be derived from satellite observations (Frankenberg et al., 2012, 2014; Guanter et al., 2012, 2013; Joiner et al., 2016) subject to dedicated space missions in the near future (Mohammed et al., 2012), finding a mechanistic relation between *T* and SIF may help revisit the study of large-scale hydrology.

Nevertheless, the relation between SIF and *T* is expected to respond to a variety of environmental factors, including water and light use efficiency (Alemohammad et al., 2017), and as such, it is potentially ecosystem-specific. Consequently, a study of the relationship between SIF and *T* based on real measurements is crucial: to the authors' knowledge, the present is the first study targeting this objective. Based on continuous measurements of SIF and *T* for a temperate mixed forest in the USA, we exploit the potential of the single SIF bands and their combinations in predicting *T* under different environmental conditions. Specifically, (1) the relationships between *T* and the selected individual SIF bands are analyzed using linear regressions, (2) the correlation between *T* and the combinations of the SIF bands is explored, (3) a nonlinear machine learning regression model is used to explore the full capacity of individual SIF bands and their combination for estimating *T*, and (4) the impacts of physiological and environmental factors on the SIF-*T* relationship are examined.

2. Materials and methods

2.1. Site description

This study is conducted in a mixed hardwood forest located in the Harvard Forest, Petersham, Massachusetts, USA (42°32′07.2″N 72°11′23.4″W). The site has the main species being American beech (*Fagus grandifolia* Ehrh), red oak (*Quercus rubra* L.) and red maple (*Acer rubrum* L.) – a mean stand age of about 80–100 years, and a mean canopy height of approximately 20–24 m. The soil is fine sandy loam on