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Assessing the effects of forest health on sun-induced chlorophyll fluorescence using the FluorFLIGHT 3-D radiative transfer model to account for forest structure

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ABSTRACT

Sun-induced fluorescence (SIF) has been proven to serve as a proxy of photosynthesis activity and therefore, as an early indicator of physiological alterations for global monitoring of vegetation. However, the interpretation of SIF over different spatial resolutions is critical to bridge the existing gap between local and global scales. This study provides insight into the influence of scene components, and forest structure and composition on the quantification of the red and far-red fluorescence signal as an early indicator of forest decline. The experiments were conducted over an oak forest (*Quercus ilex*) affected by water stress and *Phytophthora* infection in the southwest of Spain. SIF retrievals through the Fraunhofer Line Depth (FLD) principle with three spectral bands F (FLD3) was assessed using high resolution (60 cm) hyperspectral imagery extracting sunlit crown, full crown and aggregated pixels. Results showed the link between F (FLD3) extracted from sunlit crown pixels and the tree physiological condition in this context of disease infection, yielding significant relationships ($r^2 = 0.57$, $p < 0.01$) for midday xylem water potential (ψ), ($r^2 = 0.63$, $p < 0.001$) for the de-epoxidation state of the xanthophyll cycle (DEPS), and ($r^2 = 0.74$, $p < 0.001$) for leaf-level measurements of steady-state fluorescence yield (F_s). In contrast, a poor relationship was obtained when using aggregated pixels at 30 m spatial resolution, where the relationship between the image-based F (FLD3) and F_s yielded a non-significant relationship ($r^2 = 0.25$, $p > 0.05$). These results demonstrate the need for methods to accurately retrieve crown SIF from aggregated pixels in heterogeneous forest canopies with large physiological variability among individual trees. This aspect is critical where structural canopy variations and the direct influence of background and shadows affect the SIF amplitude masking the natural variations caused by physiological condition. FluorFLIGHT, a modified version of the three dimensional (3-D) radiative transfer model FLIGHT was developed for this work, enabling the simulation of canopy radiance and reflectance including fluorescence at different spatial resolutions, such as may be derived from proposed satellite missions such as FLEX, and accounting for canopy structure and varying percentage cover. The 3-D modelling approach proposed here significantly improved the relationship between F_s and F (FLD3) extracted from aggregated pixels ($r^2 = 0.70$, $p < 0.001$), performing better than when aggregation effects were not considered ($r^2 = 0.42$, $p < 0.01$). The FluorFLIGHT model used in this study improved the retrieval of SIF from aggregated pixels as a function of fractional cover, Leaf Area Index and chlorophyll content yielding significant relationships between F_s ground-data measurements and fluorescence quantum yield estimated with FluorFLIGHT at $p < 0.01$ ($r^2 = 0.79$). The methodology presented here using FluorFLIGHT also demonstrated its capabilities for mapping SIF at the tree level for single tree assessment of forest physiological condition in the context of early disease detection.

1. Introduction

Spatial and temporal estimation of photosynthesis of forest ecosystems can provide advance information on plant performance and forest dynamics in a given environment. Sun-induced chlorophyll fluorescence (SIF) has been extensively tested as a proxy of fundamental processes of plant physiology to understand the photosynthetic activity of plants and the stress development affecting photochemistry (Damm et al., 2014; Krause and Weis, 1984; Zarco-Tejada et al., 2013a). Current research efforts to monitor photosynthetic activity show a growing interest in remote sensing of the SIF signal due to its potential to be

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measured at both local (high resolution images) and global scales (medium and low resolution images) being a direct proxy of photosynthesis. The first global maps of SIF were published (Frankenberg et al., 2011; Joiner et al., 2014) using the TANSO sensor on board GOSAT (Kuze et al., 2009) allowing qualitative assessments with annual and seasonal vegetation patterns (Guanter et al., 2012). The spatial resolution provided by this sensor (10.5 km) is not, however, sufficient for the understanding of the retrieved SIF in heterogeneous vegetation canopies due to the aggregation of scene components and the large effects caused by background and shadows (Zarco-Tejada et al., 2013b). The fast development of new hyperspectral sensors to be carried on board manned and unmanned airborne platforms has given rise to the retrieval of high spatial resolution SIF at local scales, which is becoming a novel area of research (Damm et al., 2015; Zarco-Tejada et al., 2013c). However it remains very challenging to cover at very high resolution the large areas required for forest monitoring analysis. This has hitherto been the main limitation in studying physiological condition of forest canopies with higher detail, as currently available satellite sensors are limited by their spatial and spectral resolution for SIF retrieval purposes. To address this gap, the ESA's Earth Explorer Mission of the 'Fluorescence Explorer' (FLEX) (Kraft et al., 2012), the first mission designed to observe the photosynthetic activity of the vegetation layer has been recently approved, with 2022 as the tentative launch date. This mission will make possible, for the first time, the assessment of the dynamics of photosynthesis on forest canopies through SIF at 300 m spatial resolution, and with potential to distinguish different fluorescence signals from PSI and PSII (Rossini et al., 2015). This offers a great advantage over current techniques used for photosynthesis monitoring based on structural indices (e.g. the Normalized Difference Vegetation Index (NDVI)) acquired from conventional Earth-resource satellites.

The chlorophyll fluorescence signal derived from global maps is affected by illumination effects, leaf and canopy structure and composition of vegetation, and soil/background though to a lesser extent than reflectance. The interplay of within-leaf scattering properties of leaf structure and biochemical constituents are known to affect the bidirectional chlorophyll fluorescence emission (Van Wittenberghe et al., 2015, 2014; Verrelst et al., 2015). SIF flux through a leaf, upward and downward leaf chlorophyll fluorescence emissions and scattering effects have been thoroughly studied using radiative transfer models (RTMs) (Miller, 2005). However, few fluorescence models have been developed at the leaf level and even fewer are available at the canopy level, especially for the case of heterogeneous and complex canopies. The first attempts were carried as part of a vegetation fluorescence canopy model developed in the framework of the ESTEC ESA project (16365/02/NL/FF). The FluorMODleaf (Pedrós et al., 2008) and FluorSAIL (Verhoef, 2004) leaf and canopy fluorescence models were developed within the same project. FluorMODleaf is based on the widely used and validated PROSPECT leaf optical properties model and requires inputs from PROSPECT-5 plus the σII/σI ratio referring to the relative absorption cross-sections of PSI and PSII, as well as the fluorescence quantum efficiency of PSI and PSII, represented by the corresponding mean fluorescence lifetimes τI and τII. The canopy model is based on the turbid medium SAIL model (FluorSAIL) coupled with FluorMODleaf and MODTRAN to provide the illumination levels through the canopy. The Soil Canopy Observation, Photochemistry and Energy fluxes (SCOPE) model recently developed by van der Tol et al. (2009) as a means of jointly simulating directional Top of Canopy (TOC) reflected solar radiation, emitted thermal radiation and SIF signals as well as energy balance, water and CO_2 fluxes, enables vertical (1-D) modelling of integrated radiative transfer and energy balance by combining a number of intra-canopy radiative, turbulent and mass-transfer models, bearing in mind various processes involved in leaf biochemistry (Duffour et al., 2015). Using retrievals of SIF simulated with SCOPE, Verrelst et al. (2015) demonstrated that the main variables affecting SIF signal were determined by leaf optical properties and canopy structural variables with a contribution of 77.9% of the SIF total variability. Canopy re-absorption and scattering effects must be better understood and quantified. Consequently, it is very important to make progress on canopy-scale modelling approaches providing an explicit connection between the canopy biophysical processes, view and illumination geometry and the resulting canopy fluorescence signal. In light of the above, Zarco-Tejada et al. (2013b) demonstrated the need for RTM methods to accurately retrieve vegetation fluorescence signal from vegetation-soil/background aggregated pixels. Due to the lack of complex models to simulate SIF in heterogeneous canopies, Zarco-Tejada and co-authors conducted the study using a leaf-canopy fluorescence model (FluorMODleaf) combined with a geometric model to account for canopy heterogeneity (FluorSAIL) and a first-order approximation forest model (FLIM) of stand reflectance to account the effects of crown transparency and shadowing on apparent reflectance. The results demonstrated the large structural effects on the fluorescence retrieval from mixed pixels, and therefore the need to develop more complex models to account for the effect caused by the canopy architecture.

This aspect becomes particularly important in the assessment of complex forest canopies characterised by high horizontal and vertical heterogeneity (Widlowski et al., 2015). Unfortunately, currently available fluorescence models are only valid on homogeneous and uniform canopies. Strategies to simulate the spectral signature in heterogeneous forest canopies have been limited by difficulties in simulating canopy structure such as Leaf Area Index (LAI), tree density, fractional cover (FC), crown overlapping or mutual shading and multiple scattering between crowns. This paper aims to fill these gaps and in doing so to assess the potential of chlorophyll fluorescence signal retrieval as an early indicator of forest decline. The novel approach consists of coupling the leaf optical model FLUSPECT (Vilfana et al., 2016) and the three-dimensional (3-D) ray-tracing model FLIGHT developed by North (1996) to carry the scaling up approach from leaf to canopy dealing with multiple canopy components. In particular, the study aims at assessing: i) SIF as an early indicator of forest health in a heterogeneous oak forest canopy (*Quercus ilex*) affected by water stress and *Phytophthora* infection using very high resolution airborne hyperspectral imagery, ii) the canopy structure effects on the retrieval of SIF in forest canopies using a 3-D RTM, and iii) the retrieval of SIF through model inversion using coarse-spatial resolution hyperspectral imagery.

2. Materials and methods

The methods used for the assessment of SIF from hyperspectral imagery for the early detection of forest decline condition are described below, outlining field and airborne data collection, as well as the approach using the 3-D RTM FLIGHT adapted to account for fluorescence (FluorFLIGHT). In both cases, SIF was retrieved within the far-red region.

2.1. Field data collection

The experimental area is located in Puebla de Guzmán (Huelva province, in southwestern Spain) (Lat 37°36′30.89″N, Lon 7°20′27.97″W) (Fig. 1). The topography is slightly hilly, with acidic and poor soils. The annual rainfall is around 490 mm with an annual average temperature of 18.1 °C, reaching an annual average of 32 °C during summer and an annual average of 12.7 °C during winter. The vegetation is mainly composed of mature trees of the species *Quercus ilex* subsp. Bellota with an average density of 60 trees per ha (Roig Gómez et al., 2007). Since the 1990s, trees have shown symptoms of decline, leading to high mortality rates from the 2000s (Maurel et al., 2001). This region is particularly vulnerable because of the combined effect of water deficiency, soil compaction, nutrient losses, water erosion and the widespread distribution of soil-borne pathogen (*Pytophthora cinnamomi* and *Pythiumspiculum*) (Moralejo et al., 2009).

The field data measurements were conducted in 15 oak trees (*Quercus ilex* subsp. Bellota) with similar height and age located in low