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UMR Silva

PhD Thesis

Understanding the relation between photosynthesis and sun-induced chlorophyll fluorescence (SIF) of forests

Objectives

The PhD **project** aims to **understand mechanistically** the signal of **sun-induced fluorescence (SIF) above** a **forest combining** 1) **leaf-level measurements** from top to bottom of the canopy, 2) **above-canopy SIF** measurements, 3) **mechanistic** ecosystem **modelling**, **and** 4) above-canopy SIF estimates from **proximal remote-sensing**. This will **allow** us **to monitor GPP** using SIF observations **on** a variety of **different** spatial and temporal **scales** and will make it possible **to study ecosystem responses** to climate extremes **in much** more **detail** than currently possible. It will further allow us to **constrain** directly **photosynthesis in** land surface **models** instead of derived variables such as the land carbon sink.

Motivation

Current climate change is principally driven by increasing CO_2 concentrations in the atmosphere due to anthropogenic emissions. About 30% of the human emissions are absorbed by land (Friedlingstein et al., 2025). This land carbon sink is a fine balance between a large carbon uptake by **photosynthesis** from plants, also called **Gross Primary Productivity (GPP)**, and a large carbon release by respiration from plants and soils. Both, carbon uptake and carbon release are one order of magnitude larger than the current land carbon sink. Photosynthesis is, however, unfortunately not measurable directly on scales greater than a single plant. The lack of predictability of future GPP is thus one of the largest uncertainties in climate projections (IPCC, 2021).

Chlorophyll Fluorescence (ChlF) is one of the pathways how photons are used when light is absorbed by leaves and it is hence tightly linked to photosynthesis. It is measured on leaf-scale and gives deep insights into the functioning of leaves (Genty et al., 1989). Remote sensing techniques to passively detect ChlF, so-called **Sun-Induced** (or Solar-Induced) **chlorophyll Fluorescence (SIF)**, promise to access GPP via SIF. By deploying SIF spectrometers on satellites (e.g. ESA's FLEX mission to be launched in 2026), it shall allow GPP assessment at large scales (up to the planet). However, spatiotemporal variations of SIF at the top of the canopy, measured by proximal or distal remote sensing, are intricate signals of leaf-scale processes and canopy-scale radiative transfer. One has to understand firstly the biochemical signal at the leaf level and then describe well the physical radiative transfer within the canopy for different wavelengths. This has not or rarely been achieved yet. The ecosystem model SCOPE, the quasi-reference in SIF modelling, for example, implements sophisticated radiative transfer but only an empirical formulation for SIF. It was developed for homogeneous vegetation canopies such as crops and not for the more heterogenous structures of forests (van der Tol et al., 2009).

SIF is, however, currently becoming the reference in studies of the global carbon cycle and in assessing the response of GPP to environmental cues. This is grounded on the empirical basis that remotely-sensed SIF from satellites correlates well with estimated GPP on eddy covariance flux towers on a monthly scale. This correlation breaks down completely if one descends below a resolution of about 10 days (Shan et al., 2019).

The PhD project wants to understand the observed SIF above a complex canopy and how it relates to photosynthesis of the forest. Can we go beyond pure correlations with GPP? Can we understand the diel SIF signal and how it is related to GPP? Is there a unique relation between above-canopy SIF and GPP? How representative is the small footprint of the SIF sensor compared to the footprint of the heat, water vapour and CO_2 flux signals?

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The **project uses model-data fusion** to answer these questions, **combining** a detailed **mechanistic vegetation model with observations from** a **newly-developed instrument for active and passive SIF on** the **leaf level**, state-of-the-art **above-canopy SIF**, experimental **drone-based SIF** observations, **and** heat, water vapour, and CO_2 flux measurements on an **eddy covariance** tower. It is **integrated in** the international **project FLORES**, in which satellite observations will be evaluated against observations of the current project and continental land surface modelling will transfer the mechanistic modelling approach of the current project to larger scales.

Methods

The project can be divided into four main steps that are: 1/ measurements along the vertical canopy gradient of leaf-level parameters for the mechanistic light response model (MLR) for photosynthesis and SIF; 2/ the implementation of SIF in the ecosystem model MuSICA; 3/ the interpretation of the above-canopy SIF signal with MuSICA; and 4/ the analysis of the spatial representativity of the local above-canopy SIF signal for the larger ecosystem.

Work package 1 – Leaf-level measurements: A hand-held instrument was assembled in 2025, which combines a gas exchange system LI-6800 with a Multiphase Flash Fluorometer for measuring photosynthesis and active chlorophyll fluorescence ChlF, and a VIS-NIR high-resolution spectrometer for passive ChlF, i.e. SIF.

Two measurement campaigns are planned for summer 2027 and summer 2028 at the beech forest FR-Hes (57)., which is a class 1 ICOS site (www.icos-cp.eu) with a full set of eddy covariance system and associated meteorological variables at the highest international standards. The first campaign will concentrate on all variables and response curves to parameterise the ecosystem model MuSICA along the vertical canopy gradient. The second campaign will concentrate not only on the vertical gradient but also on the horizontal variability within the forest canopy.

The first campaign in June/July 2027 will determine vertical gradients of photosynthetic parameters, leaf properties, and ecosystem structure within the forest canopy, following a protocol established during an on-going PhD thesis. Measurements will allow to parameterise the mechanistic light response (MLR) model of SIF and photosynthesis (Beauclaire, Vanden Brande, et al., 2024).

The second measurement campaign in June/July 2028 will be in parallel with measurements by the drone-based SIF system (University of Antwerp). It will focus on vertical gradients and horizontal variability. It will further determine parameters that might turn out to be sensitive in the enhanced ecosystem model MuSICA (cf. WP2).

Work package 2 – Modelling SIF: The ecosystem model MuSICA (Gennaretti et al., 2020) will be enhanced to calculate SIF in addition to CO_2, water, and heat fluxes using the mechanistic light response (MLR) model as enhanced by the project partners (Beauclaire, Vanden Brande, et al., 2024). Application of the enhanced MLR uses a fitting parameter (the light escape probability f_{esc}) that represents radiative transfer in the structured ecosystem (Beauclaire, De Cannière, et al., 2024). Radiative transfer is modelled directly by MuSICA. The sophisticated radiative transfer scheme of MuSICA (Sinoquet et al., 2001) will be enhanced by the specific wavelengths for SIF.

MuSICA is a multi-layer, multi-species ecosystem model (Ogée et al., 2003), which is adapted for measurements of eddy covariance flux towers such as installed at FR-Hes. It has not a 3D structure modelling individual trees but treats the ecosystem as a layered 1D system. Model complexity and scale is hence in-between the very detailed 3D SCOPE model (van der Tol et al., 2009) and large-scale land surface models (e.g. Bacour et al., 2019). It has, however, some specifics that go beyond the SCOPE model such as the ability to deal with several plant species, a mechanistic description of photosynthesis, and plant hydraulics linking soil water potentials with stomatal conductance. We consider that it could be the missing link between existing SIF models, improving parameterizations at large, continental scale.

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Work package 3 – Understanding above-canopy SIF: An instrument for automatic acquisition of SIF (FloX, JB Hyperspectral Devices, Germany) with a second spectrometer and a tilt unit was installed recently at the flux site FR-Hes. FloX will give continuous SIF measurements representing about 50 m^2 of forest canopy (with the tilt unit). The enhanced ecosystem model MuSICA from WP2 will be used to understand the diurnal variations of SIF observed above the canopy.

The parameters in MuSICA will influence not only the absolute values of SIF but also its dynamic range over the course of the day. The sensitivity analyses of WP2 thus need to cater for different output signals (Cuntz et al., 2015, 2016). The implementation of SIF in MuSICA (WP2) will hence be a priority task right from the start of the thesis.

Work package 4 – Spatial variations of SIF: The above-canopy instrument (FloX) observes an area of less than 50 m^2, compared to the footprint of about 1 km^2 of the flux observations. Here, a new drone-based SIF instrument will be employed to measure the spatial heterogeneity of SIF in the footprint of the flux tower. Such an instrument does not exist yet because the fluorescence is a very small signal on a large background so that one needs relatively long integration times. However, the project FLORES works together with the manufacturer JB Hyperspectral Devices (Germany) to develop a drone-based SIF instrument, the so-called AirFloX. Partners from the University of Antwerp and from the University of Liège will join the measurement campaign at FR-Hes to operate a wide array of UAV-based instruments including a thermal camera, a hyperspectral camera, and a LiDAR. This will refine not only data interpretation but will also lead to model refinement because of different sensitivities of different variables to specific model parameters.

Applications

We are seeking a motivated candidate that likes to combine biology with physics, i.e. combining biochemical modelling at the leaf level with physical modelling at the canopy scale. All quantitative analyses will use mechanistic modelling with MuSICA so strong computer skills and an aptitude for physics will be required. As the project uses model-data fusion, active participation in two measurement campaigns will be essential. There should be an interest in research related to climate change and an affinity to work with international partners.

The thesis will take place for three years at the UMR Silva on the campus of INRAE near Nancy (54280 Champenoux) from autumn 2026 onwards.

To apply, please send a cover letter, a CV, the transcript of grades of the master (or of the 3 years of engineering school), a contact information of an academic reference, as well as a résumé (300 words) of the master topic (or of the end-of-study internship) to Matthias Cuntz – matthias.cuntz@inrae.fr

Interviews will take place in June.

Do not hesitate to contact us for any further information.

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