→ INTERNATIONAL NETWORK ON REMOTE SENSING OF TERRESTRIAL AND AQUATIC FLUORESCENCE

ABSTRACT BOOK

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3. Abstracts

Atmospheric correction and fluorescence retrieval over land and water

Global Retrievals of Solar-Induced Chlorophyll Fluorescence With TROPOMI

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The recently launched TROPOspheric Monitoring Instrument (TROPOMI) is designed to monitor atmospheric trace gases and air pollutants with an unprecedented resolution in space and time. In addition, TROPOMI's spectral coverage, resolution and radiometric accuracy also permit us to retrieve solar-induced chlorophyll fluorescence (SIF) in both red and far-red wavelength. In this contribution, we will present our retrieval approach along with the lessons learned from the first year of TROPOMI SIF data. TROPOMI's notable radiometric performance in combination with its wide swath (allowing for almost daily surface coverage), and ground pixel size of about 7 km x 3.5 km (at nadir) largely outperforms previous and existing capabilities for a spatial continuous monitoring of SIF from space. However, interpretation requires caution, as the broad range of viewing-illumination geometries covered by TROPOMI's 2,600-km-wide swath needs to be taken into account. We will further present an intersensor comparison with OCO-2 (Orbiting Carbon Observatory-2) SIF, showing excellent agreement and underscoring the high quality of TROPOMI's SIF retrievals.

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FLEX Level-1b to Level-2 data processing chain. Project overview and validation results

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ESA's FLEX/Sentinel-3 tandem mission aims at mapping Sun-induced fluorescence (SIF) as a proxy to quantify photosynthetic activity of terrestrial vegetation. Due to the complexity of the mission concept and stringent requirements for the data processing algorithms, ESA developed an End-to-End Mission Performance Simulator (E2ES) tool to reproduce the expected mission performance and consolidate the whole data processing chain.
The development and optimization of the Level-2 data processing chain plays an important role in the preparatory activities for the future Ground Segment development. An on-going 2-years ESA/ESTEC project aims at developing this Level-2 processing chain for its integration and validation into the FLEX E2E simulator. The L2 data processing chain consists in four modules:
L2A: creating a synergistic product by co-registering and cross-calibrating FLORIS (FLEX) and OLCI/SLSTR (Sentinel-3) instruments,
L2B: characterizing the atmospheric state (water vapor and aerosol optical properties) and inverting the surface apparent reflectance for all mission instruments,
L2C: retrieving SIF emission from terrestrial vegetation by a state-of-the-art spectral fitting method, and
L2D: determining vegetation biophysical parameters for a complete interpretation of the SIF signal.

The FLEX L1B to L2 Algorithms Development study is leaded by Magellium (France) with the universities of Valencia (Spain), Bologna and Milano-Bicocca (Italy) as subcontractors.

The goal of this presentation is to give an overview of the project activities and current status to the scientific community in the field of remote sensing of fluorescence. In this presentation, we will also describe the entire L2A-to-L2D data processing chain, and demonstrate the current accuracy of the implemented algorithms through the latest performance assessment results.

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Retrieval of the Sun-Induced Fluorescence in the framework of the FLEX mission

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The FLuORescence Imaging Spectrometer aboard of the FLEX satellite is specifically designed to provide radiance observations in high-spectral resolution (0.3 nm) around the O2 bands, together with a broad spectral coverage from 500 to 780 nm. This specific configuration was designed with the aim to: i) observe the red and far-red fluorescence at the O2-B and O2-A bands, or even the full SIF spectrum; ii) provide canopy chemical/physical variables essential to interpret the SIF (i.e., Leaf Area Index (LAI); Leaf Chlorophyll Content (LCC); Fraction Of Absorbed PAR (fAPAR), etc.) and the PRI. This set of measurements will be further complemented from the information provided by the Ocean Land Color Imager (OLCI) and the Sea and Land Surface Temperature Radiometer (SLSTR) instruments aboard of the Copernicus Sentinel-3 (S-3) mission. The S-3 will fly in tandem to FLEX providing all the key information required to characterize the atmosphere with the accuracy required to retrieve SIF at the O2 bands and Solar Fraunhofer lines. This specific set-up will offer a number of improved capabilities compared with the observations available by current satellites (e.g., OCO-2, TROPOMI etc.), such as the possibility to spectrally resolve the entire SIF spectrum in the 670-780 nm range.

This contribution aims to describe the overall concept of the full SIF spectrum retrieval algorithm and the ongoing development and testing activities on different sensors. The algorithm is a revised approach of the original version proposed in Cogliati et.al., 2015, where the major improvement was the possibility to model/fit the SIF spectrum with a very limited number of parameters. The algorithm, initially developed on radiative transfer simulations, has been further adapted to retrieve the fluorescence from ground and airborne spectrometers. In this contribution we will first show how the algorithm is going to be implemented within the FLEX L2 processor under development in the framework of the ESA's FLEX-L2RM project. Specifically, the SIF retrieval algorithm is part in the so-called L2C module of the FLEX L2R. It makes uses a set of input variables produced by the L2A (spectral/radiometric calibration) and L2B (atmospheric correction) modules to retrieve SIF spectrum and a set of metrics (i.e. SIF values at O2-A and O2-B, SIF at the maximum of the red and far-red peaks, wavelengths of the maximum and spectrally integrated SIF). A first evaluation of the accuracy obtained by the retrieval algorithm was evaluated on radiative transfer simulations obtained by coupling the SCOPE and MODTRAN5.

The retrieval algorithm was further adapted to process the airborne imagery acquired collected by the high-resolution imaging spectrometer HyPlant. A set of flight-lines collected during the recent FLEXSense campaign carried out in 2018 were processed by the novel algorithm and analyzed in comparison with ground-based spectral measurements. For the first time we were able to observe the full SIF spectrum of different crop fields (e.g., corn, alfalfa) and in general of the diverse land-cover types in the study areas, as well to observe the temporal evolution along the summer time period of the campaign (June-August). The resolved fluorescence spectrum observed for the different land cover types shows an extremely diverse spectral behavior that it is function of a large number of physiological and chemical/physical variables the different canopies. Finally, we assessed the accuracy of the full fluorescence maps produced by a direct comparison with the SIF spectra obtained by the ground-based spectrometers (FLOX instruments) collected simultaneously to the airborne overpasses.

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From proximal sensing to satellite scale: Analyzing and compensating atmospheric effects on oxygen features for retrieving fluorescence.

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In the forthcoming years, satellite-derived photosynthesis research will be advancing with the advent of the ESA's FLuorecence EXplorer (FLEX) mission. Among other vegetation-related products, FLEX aims to provide continuous measurements of Sun-Induced vegetation chlorophyll Fluorencence (SIF) from 650 nm to 780 nm at the high spatial resolution of 300 m. In this context, SIF estimations acquired at a lower scale, either from systems mounted on towers, Unmanned Aerial Vehicles (UAVs) or airborne platforms, will become essential for FLEX – or any other fluorescence-related mission – preparatory activities and validation campaigns.

Regardless of the vertical scale, proximal sensing or satellite level, when retrieving SIF by especially resolving the strong oxygen (O_2) absorption features, atmospheric effects must always be compensated. To this end, this work provides an overview of the most important aspects to be accounted for as part of the atmospheric correction process across contrasting vertical scales. In particular, we stress those key points related to the atmospheric characterization, the algebra involved, and the possible usage of the surface apparent reflectance as a quality indicator.

Thus, this work starts with a comprehensive analysis about how atmospheric effects impact SIF estimations on proximal sensing, thereby studying the influence of: (1) the sensor height above the vegetated canopy; (2) the SIF retrieval technique used, e.g., Fraunhofer Line Discriminator (FLD) family or Spectral Fitting Methods (SFM); and (3) the instrument's spectral resolution. For proximal–sensing scenarios, we demonstrate that compensating for atmospheric effects by simply introducing the O_2 transmittance function into the FLD or SFM formulations improves SIF estimations. However, due to the algebra assumed these compensation strategies still derive some inaccuracies within the absorption regions.

Looking towards a more rigorous atmospheric compensation strategy, this work also assesses the pros and cons of adapting a classic airborne atmospheric correction scheme to SIF proximal-sensing applications, e.g. addressed to systems mounted on towers or UAVs. In addition, given the importance of O_2 absorption in the SIF retrieval process, SIF retrieval dependency on surface pressure (p) and air temperature (T) is also evaluated, paying special attention to those applications acquiring long temporal data series subjected to abrupt changes in meteorological conditions.

Finally, since inaccuracies on the atmospheric correction process make SIF rapidly prone to errors, this work will close with a final discussion on the exploitation of the surface apparent reflectance across different vertical scales as a robust quality indicator.

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Applications of fluorescence in stress detection

Understanding the spectral changes associated to the photoprotection (NPQ) mechanisms of vegetation: Opportunities for FLEX-FLORIS LR (500-780 nm) products

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With ESA's upcoming Fluorescence Explorer-Sentinel 3 tandem mission (FLEX-S3), not only the retrieval of solar-induced fluorescence (F) becomes a new opportunity for understanding plant functional behaviour, also the photoprotection dynamics can potentially be further understood. The Fluorescence Imaging Spectrometer Low Resolution (FLORIS LR) on board of FLEX will cover the 500-780 nm range with a bandwidth between 0.1 nm and 2 nm, and a 1 nm spectral resolution in the region of photoprotection dynamics (500-740 nm). Photoprotection or controlled non-photochemical energy quenching (NPQ) and F emission are the two processes controlling the electron transport to the photosynthesis reaction centres and are therefore indispensable for the development of Level-2D higher-level photosynthesis products for the FLEX-S3 mission.

To safely balance out the energy supply to the photosynthetic reaction centres, the photosynthesis apparatus switches efficiently between a light harvesting to a photoprotective mode in different steps. These different controlled regulated heat dissipation mechanisms are activated inside the leaves by various physical and biochemical triggers. The spectral characterization of these NPQ mechanisms is challenging due to several overlapping mechanisms taking place on a diurnal scale. Besides the absorbance feature related to the chemical xanthophyll conversion, several additional overlapping NPQ absorbance features are present in the vegetation spectrum. Strong conformational pigment bed changes appear to be responsible for a significant absorbance change in the VIS-NIR range. The characterization of these spectral absorbance features is a further step in the understanding of dynamic plant behaviour regarding its energy distribution, i.e. with a harvesting or a dissipation fate. Current scientific developments in the spectral characterization of the NPQ mechanisms are presented, being, in combination with F retrieval, of a high importance for assessing vegetation photosynthesis from remote sensing.

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Active and passive fluorescence measurements under elevated CO2 the field.

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The increase of atmospheric CO2 concentration [CO2] has a direct effect on photosynthesis and plant production. To study the effect of predicted [CO2] increase in the field Free Air CO2 Enrichment (FACE) experiments have been developed. These FACE experiments typically control [CO2] around 550 ppm and have measured plant performance in diverse ecosystems. In the agricultural ecosystems FACE experiments have shown often a significant increase in yield whereas quality may decrease.

Yield and quality are key traits to select for new varieties by breeders but they are breeding under lower [CO2] then when new varieties will be released under current [CO2] increase predictions. To test (new) variety performance the BREEDFACE was set up by Forschungszentrum Juelich IBG-2 Plant Sciences in Campus Klein-Altendorf Germany. BREEDFACE allows growth of crops combined with quantifying plant traits with a large range of field phenotyping techniques.

In this presentation we will focus on active and passive fluorescence measurements by two sensors, the Light Induced Fluorescence Transient (LIFT) device and the Fluorescence Box (FLOX) respectively. The LIFT device retrieves fluorescence at 680 nm after activation by blue (470nm) light by a saturating sequence of flashlets at high repetition rates. The FLOX enables passive measurements of sun induced fluorescence (SIF) in the atmospheric oxygen absorption bands at 689 and 760nm. Both instruments were used to measure winter wheat in early cold spring and to study soybean varieties grown under elevated and ambient [CO2] on a hot summer day in 2018. Winter wheat varieties were chosen from an historic collection released from 1950 to 2013. Two to four soybean varieties were chosen out of 18 varieties because of their contrasting photosynthetic efficiency (Fq'/Fm') performance under elevated [CO2] measured in July 2018 by LIFT.

In winter wheat, active and passive fluorescence varied with temperature changes in early spring and Fq'/Fm' and SIF yield at 750 nm were positively correlated. In soybean, passive fluorescence differed between two soybean varieties when grown under elevated [CO2] in August. The effect of elevated [CO2] will be discussed between and within species. In the latter the special focus will be on the potential of using fluorescence as plant trait for phenotyping.

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Calibration and validation of satellite data

Radiometric/spectral calibration and co-registration correction algorithms for FLEX/Sentinel-3 Level-2 synergy

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In the context of ESA's FLEX/Sentinel-3 mission Phase C/D activities, an on-going 2-years project aims at consolidating and validating the Level-2 data processing chain. The retrieval of the L2 geophysical products from the FLEX/Sentinel-3 tandem mission, and in particular the fluorescence retrieval, relies on measurements from the FLORIS, OLCI and SLSTR instruments. The Level-1b products of these instruments have to be harmonized with respect to their geolocation, spatial resolution, and spectral information to ensure consistent input data to the L2 retrieval algorithms. Among the components of the L2 processing chain, the L2A module has a key role of harmonizing the FLEX/Sentinel-3 Level-1b products, ensuring the consistency between the various instruments for a correct execution and accuracy of the next retrieval modules. The L2A module which is divided in the following steps:

(1) Preliminary atmospheric characterization: extracts meteorological data from existing datasets (S3 products and ECMWF data) and derives a preliminary cloud mask from S3 L1B.

(2) Geometric co-registration: refines the geometric models of FLORIS images (from the FLORIS-HR and -LR instruments), so that they could match together and with Sentinel-3 acquisitions.
(3) Radiometric cross-calibration: calculates and applies radiometric gain ratios by cross-calibration between FLORIS and OLCI at different spectral bands, harmonizing the radiometry of FLORIS, OLCI and SLSTR instruments.
(4) Spectral-recalibration: the correct characterization of the FLORIS ISRF is required in order to minimize error propagation in the following L2 processing (particularly in the atmospheric correction within the narrow O2 bands). The algorithm, based on the use of solar and O2 absorption lines as reference, aims at reducing the uncertainties of the on-ground ISRF characterization and of the in-flight distortions.
(5) Final ortho-rectification: re-projects the inter-calibrated products into a common ground grid.

This paper will give first an overview of the on-going activities involving the generation of the Level-2a synergy data product. Secondly, we will focus on the algorithms description for spectral re-calibration and radiometric cross-calibration of the FLORIS, OLCI and SLSTR measurements. Finally, we will show validation and performance assessment results.

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Copernicus GBOV service: a support to FLEX products validation

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GBOV (Ground-Based Observations for Validation; http://gbov.copernicus.acri.fr), part of Copernicus Global Land Service (CGLS) is dedicated to the long term validation of land products derived from satellite borne sensors. Its prime objective is to facilitate the use of ground observations acquired from operational monitoring networks and their comparison to Earth Observation products providing ready to use up-scaled product derived from consistent and documented procedures. GBOV service as the following objectives:

- Collecting multi-year ground-based observations of high relevance for the understanding of land surface processes from existing global networks. These ground-based observations are collected over a series of selected sites operated by international networks such as FluxNet, NEON, OZFlux, SurfRad, TERN, USRCN, AERONET, ARM, BSRN …;
- Upgrading existing sites with new instrumentation or establishing entirely new monitoring sites to close thematic or geographic gaps;
- Implementing and maintaining a database for the distribution of reference measurements (RMs) and the corresponding Land Products (LPs).

GBOV service is primarily directed at the validation of selected CGLS products (top-of-canopy reflectance, surface albedo, leaf areas index, fraction of absorbed PAR, fraction of vegetation cover, land surface temperature and soil moisture), providing collections of multiple-year ground-based RMs as well as derived LPs. The Earth Explorer - Fluorescence Explorer (FLEX) mission will map vegetation fluorescence to quantify photosynthetic activity. Among the standard products to be generated by FLEX ground segment: LAI and FAPAR are among the validation products delivered by GBOV service. This talk will present the GBOV infrastructure and provide an overview of the services and products offered as well as its potential for FLEX validation.

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Validation of Sentinel-2 cloud masking and classification products – potential for Sentinel-3 validation?

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The Copernicus Sentinel-2 mission is a constellation of two polar orbiting, optical satellites Sentinel-2A and Sentinel-2B delivering high spatial resolution data products. This mission is dedicated to land monitoring, emergency management and security. In particular, it finds applications in land-cover change analysis, retrieval of biophysical variables, monitoring of coastal and inland waters as well as risk and disaster mapping.

Since June 2017 the Copernicus Sentinel-2 mission is fully operating while since March 2018, Level-2A products are generated by the official Sentinel-2 ground segment (PDGS) and are available on the Copernicus Open Access Hub within 12 hours of sensing time. The Level-2A processor for Sentinel-2 data – Sen2Cor – corrects monotemporal Level-1C Top-Of-Atmosphere products from the effects of the atmosphere in order to deliver a Level-2A surface reflectance product. The basic framework consists of two main modules: the Scene Classification (SCL) and the Atmospheric Correction (AC). The SCL algorithm allows to detect

clouds, their shadows and snow, and to generate a classification map with 11 classes. This map is used internally in Sen2Cor in the AC module to distinguish between cloudy, clear and
water pixels, but it does not perform a land cover classification map in a strict sense.

In the frame of the ESA Sentinel-2 Mission Performance Center (MPC), the Level-2A validation strategy and operational validation service is performed to ensure the highest quality of provided Level-2A products. The presentation gives an overview of the different steps of the Sen2Cor Scene Classification algorithm and its validation procedure. Validation results on some selected products as well as the current limitations of the algorithm are presented. Finally, potential synergies between Sentinel-2 and Sentinel-3 cloud screening validation are addressed.

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Airborne and UAS campaigns

Collaborative Solar-induced fluorescence measurement campaigns – decsription of objectives, ground / airborne measurements and preliminary results

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A number of multi-site campaigns were funded by ESA in 2018 to gather new data on plant fluorescence under different climates, seasons and land uses. A first project (AtmoFlex) was designed to acquire Solar Induces Fluorescence (SIF) by means of a series of spectrometers (FloxBox, JB, D) that were deployed in the field in Italy, Germany, France and Spain. The Italian and German sites were focused on long-term continuous SIF observations on crops and grasslands, the French site was on a deciduous oak forest (Quercus pubescens) and the Spanish site was installed over a typical Dehesa land use made by a combination of grasslands and sparse holm oak trees. SIF data acquisition at high temporal resolution started in January 2018 and is still on going at all sites. This presentation will summarize and discuss the different datasets that are becoming available while other presentations will focus specifically on some key findings of the AtmoFlex campaign.
This first campaign was then nested to a second ESA-funded project in the summer 2018, called FlexSense. During such campaign during which several hundred flight lines across five European core sites were recorded with the high resolution airborne imaging spectrometer HyPlant_3, which has improved optical performance in comparison to the version flown the years before. HyPlant_3 was mounted with an aligned TASI sensor for thermal and a LIDAR sensor for 3-D surface mapping on board a Cessna aircraft. HyPlant images were acquired with different flight modes that include low-altitude flights for high-resolution spatial mapping and high altitude larger scale mapping in synchrony with a constellation of Sentinel 3A and Sentinel 3B to better understand the influence of atmospheric properties onto fluorescence retrieval. Thanks to the exceptional weather conditions in June and July 2018, characterized by clear skies conditions, we were able to record an unique data set of various stressed and non-stressed vegetation types. A flexible campaign planning enabled the use of this airborne package at different sites, covering clear sky conditions and facilitated the synchronous data acquisition with various ground activities and other airborne platforms such as APEX and AVIRIS NG. This presentation, will provide an overview on the available data by illustrating the first maps of solar-induced fluorescence from HyPlant_3. For the first time we could apply the spectral fitting method (SFM), which will be the nominal retrieval method for the FLEX satellite mission, for a larger set of HyPlant_3 images. This retrieval method uses a carefully parameterized atmospheric correction and a retrieval of both fluorescence peaks around the oxygen absorption bands. Maps of solar-induced fluorescence are registered with images of land surface temperature, structural vegetation properties, and detailed ground-based measurements of the functional status of various vegetation types. The dynamic changes in the solar induced fluorescence and information that is contained in the two peak feature of

fluorescence is discussed on the background of the functional acclimation of vegetation to diurnal, seasonal and stress induced changes for which the summer month in 2018 provided ideal conditions.

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Quantitative assessment of Sun-Induced-Fluorescence maps from HyPlant airborne images using different quality criteria - Part I

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The ability to investigate the Earth's environment will be largely improved by hyperspectral satellite data. The FLuorescence EXplorer (FLEX) will be the first hyperspectral mission designed to monitor the photosynthetic activity of the terrestrial vegetation layer by using a completely novel technique measuring the sun-induced chlorophyll fluorescence (SIF) signal that originates from the core of the photosynthetic machinery. In preparation of the upcoming FLEX satellite mission that will be launched in 2022, a large field campaign, namely FLEXSense, was conducted in summer 2018 including representative study sites at several locations in middle and south Europe as well as North America.

During the various field activities, airborne data were acquired with the hyperspectral airborne imager HyPlant that consists of two sensor heads. The DUAL module is a line-imaging push-broom sensor providing contiguous spectral information from 370 to 2500 nm. The FLUO module measures radiance in high spectral resolution (0.25 nm) in the spectral region of the two oxygen absorption bands covering a range from 670 to 780 nm and facilitates a reliable retrieval of the chlorophyll fluorescence signal. Currently, two different algorithms are routinely used to retrieve red (SIF680) and far-red SIF (SIF760) from HyPlant data. Both methods exploit the oxygen absorption bands for the retrieval. While the improved Fraunhofer Line Depth (iFLD) approach employs a semi-empirical atmospheric correction (i.e. using bare soils), the Spectral Fitting method (SFM) is coupled with a physically-based atmospheric correction (MODTRAN5 code).

A common method of testing the reliability of remotely-sensed SIF (in this study airborne maps) is the comparison with "ground truth" data. In many cases, however, ground measurements of SIF are not available or are too labor-intensive to be measured at regional level. For this reason, we developed an alternative approach based on different image criteria to assess the quality of airborne SIF maps. The set of quality criteria (e.g. signal-to-noise ratio, correlation with vegetation indices, plausibility checks, etc.) helps identifying and quantifying errors and artifacts in retrieved SIF maps.

In this contribution, we outline the defined set of quality criteria and demonstrate their capability to determine the quality of individual SIF maps derived from HyPlant images acquired during the 2018 FLEXSense campaign. The application of the proposed quality features proved to be a valuable tool for assessing the quality of SIF maps derived from HyPlant airborne data. We suggest to apply this set of criteria in addition to validation attempts that employ ground reference measurements. This allows providing complementary information about the SIF retrieval accuracy and the quality of entire SIF maps.

Since the quality assessment using the different criteria is very extensive, only a part will be covered in this talk while the remaining criteria and their application will be presented in form of a poster (additional contribution: V. Krieger; B. Siegmann; M. Matveeva; P. Rademske; P. Heid; L. Grünhagen; O. Muller; S. Cogliati; A. Damm and U. Rascher – Quantitative assessment of Sun-Induced-Fluorescence maps from HyPlant airborne images using different quality criteria - Part II)

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UAS-based Chlorophyll Fluorescence Measurements of Barley Canopies – Results from FLEXSense 2018

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This study presents the first multiscale SIF dataset, where field and airborne observations are accompanied by unmanned airborne system (UAS) measurements. A dataset of diurnal UAS-spectroscopy for retrieval of solar-induced chlorophyll fluorescence (SIF) was acquired in June 2018 during the FLuorescence EXplorer (FLEX) calibration/validation campaign (FLEXSense 2018). While preparation of the FLEX mission is in progress, airborne, drone and ground data collected simultaneously with Sentinel 3A and Sentinel 3B are expected to contribute to a better understanding of the fluorescence signal and retrieval techniques across different spatial mapping scales. The UAS-based system presented here, called AirSIF, is built on a dual optical pathway and a high resolution spectroradiometer installed on a low-altitude multi-rotor remotely piloted platform. The spectroradiometer acquisitions are synchronised with readings of an on-board Inertial Measurement Unit (IMU)/ Global Navigation Satellite System (GNSS) system, which enables to reconstruct geometrically and spatially explicit footprints of the spectroradiometer SIF measurements during a flight. The study was conducted at a plant breeding and field trial agricultural station in Western Germany, near Bonn. 11 summer barley experimental plots of a size of 3 x 6 m were monitored diurnally within four UAS flights carried out between 12:00 and 17:00 local summer time. A hovering style of UAS data acquisition (named “stop and go”) allowed us to assess the stability of SIF values retrieved from footprints over the experimental plots (n = 119). Each plot was set as a waypoint in the UAS flight path. The UAS was flown at 8 m above ground level at 1.5 m/s ground speed. Upon reaching the waypoint, the UAS hovered above a plot for 15 seconds while the spectroradiometer acquired data continuously. Between one and six measurements were taken of each plot per flight. The resulting spectroradiometer footprints varied from 0.5 to 2.5 m² in size, depending on UAS actual position drifts during hovering. The SIF values measured have a mean of 0.83 mW.m-2.nm-1.sr-1, a median of 0.84 mW.m-2.nm-1.sr-1, and standard deviation of 0.59 mW.m-2.nm-1.sr-1. The values are being analysed and will be compared against ground-based FLOX box measurements, collected for some experimental plots just before and after UAS acquisitions, and SIF retrieved from 1 m ground resolution airborne Hyplant_3 image data, acquired almost simultaneously.

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In situ measurement of fluorescence I

FluoSPECCHIO: A spectral data base system to facilitate a validation network for the upcoming Fluorescence Explorer (FLEX) mission

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The upcoming satellite mission Fluorescence Explorer (FLEX), currently under development by the European Space Agency, will provide after its launch in 2022 global information of fluorescence and photosynthetic activity. Coherence of fluorescence observations from in-situ, airborne, and satellite platforms for different ecosystems is key to retrieve robust novel plant physiological information form this new data source. The complexity and information content of observed fluorescence signals, however, changes with observational scale and challenges comparability of such measurements. In situ measurements, for example, are representative for small surface areas and are collected in close distance to the surface with high temporal resolution (minute based). Satellite observations are able to collect fluorescence emissions of large areas but lack temporal resolution (monthly based).

We present the design and function of the centralised data base system FluoSPECCHIO, which is an extension of the spectral information system SPECCHIO (www.specchio.ch). The development of this system was triggered by the need for a coherent strategy to obtain cross scale (both temporal and spatial) fluorescence measurements stemming from a growing network of in-situ measurements distributed across a diversity of ecosystems and an increasing number of airborne and satellite platforms. The database facilitates ingesting point observations by the Fluorescence Box (FLOX) manufactured by JB Hyperspectral Devices, currently establishing a standard for a fast growing in-situ network of measurement sites worldwide.

We demonstrate the functioning of the data base system including its capability to autonomously read and process FLOX data. We outline possibilities for how FluoSPECCHIO can facilitate the development of a validation network for the upcoming FLEX Sentinel-3 mission.

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Filtering Fluorescence Time Series Acquired with the FloX Monitoring Field Spectrometer for the Investigation of Vegetation Dynamic Seasonal Trends over Grassland

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The process of photosynthesis feeds almost all living organisms on the planet, plays an important role in the global carbon cycle and directly impacts the climate on earth. Remote sensing of sun induced chlorophyll fluorescence (SIF) is applied for non-invasive monitoring of photosynthesis in terrestrial vegetation on various scales. However, the direct understanding of SIF as a proxy for photosynthesis is a field of ongoing research. Tower-based SIF retrieval by field spectrometers for autonomous long-term observation of vegetation contributes to gain further insight into ecosystem-specific seasonal dynamics of photosynthesis activity.

In this work we investigate quality criteria for long-term SIF measurements collected with FloX monitoring field spectrometers (JB Hyperspectral Devices, Düsseldorf, Germany) based on instrument characteristics, calibration, performance parameters and setup. Based on these derived quality criteria, we propose a filtering protocol for SIF data retrieved with the FloX monitoring field spectrometers. Furthermore, the impact of changing diffuse light ratio on seasonal trends of SIF Yield is investigated and shown to be neglectable within time series. Seasonal trends of midday-mean, filtered, apparent SIF Yield are examined over grassland in Germany during spring 2018 based on FloX data. We relate apparent SIF Yield with the help of vegetation indices (VI) to phenological and physiological changes at canopy level. This research indicates that filtered, apparent SIF Yield monitors in combination with VI phenological and physiological changes of grassland at canopy level in response to rising temperatures during spring.

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Retrieval of biophysical parameters from FLEX and Sentinel-3 data

Status on the retrieval models for the traditional biophysical variables (LAI, Cab, fAPAR, FVC and APAR)

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The biophysical parameters will be retrieved by use of a hybrid method combining a non-parametric Machine Learning Regression Algorithm (MLRA) and a vegetation Radiative Transfer Model (RTM). OLCI (imaging spectrometer on Sentinel-3) and FLORIS (hyperspectral imager on FLEX) Top-Of-Canopy (TOC) reflectances are simulated with the RTM SCOPE and subsequently injected with a specific amount of Gaussian white noise to account for the natural variability existing within the 300m-pixels of the FLEX-Sent-3 tandem mission. The resulting database of vegetation properties and corresponding TOC reflectances, covering a wide range of geometrical configurations and canopy realisations, is then used to train the MLRA Gaussian Process Regression (GPR) and generate the retrieval models. These models are based on either OLCI spectra alone, on FLORIS spectra alone, or on the combined spectra of both instruments. Several steps in the retrieval procedure can be optimized in order to provide enhanced model predictions: the range of the input variables of SCOPE, the size of the training database and the amount of noise. At present, the models are optimized using SCOPE simulated reflectance spectra. In a second step, when close-to-real atmospherically-corrected images coming from the FLEX End-to-End Mission Performance Simulator will be available, a more accurate noise estimation will enable further model optimization. The first version of the retrieval models for Leaf Area Index (LAI), Leaf Chlorophyll Content (Cab) and fraction of Absorbed Photosynthetically Active Radiation (fAPAR) were validated on reference images which are simulated with an in-house developed Automated Scene Generator Module (A-SGM) scientific toolbox. For Cab retrieval, the OLCI spectral data alone give reasonable model performances despite the limited number of bands involved (R^2: 0.90; relative RMSE: 14.0%). Conversely, the use of FLORIS data alone improves greatly the results (R^2: 0.97; relative RMSE: 8.9%). Further, merging the OLCI and the FLORIS spectra does not significantly improve the results (R^2: 0.96; relative RMSE: 8.5%). Regarding LAI retrieval, the improvement of the model performances by using only FLORIS spectra (R^2: 0.82; relative RMSE: 30.7%) rather than only OLCI spectra (R^2: 0.81; relative RMSE: 32.0%) is less obvious but the synergy of both datasets is more advantageous (R^2: 0.87; relative RMSE: 27.0%). The models for the retrieval of fAPAR, regardless of on which dataset they are based, are performing particularly well (average R2: 0.96; average relative RMSE: 7.3%). APAR on the other hand, will be predicted from the fAPAR model by multiplying the fAPAR estimations with PAR, which will be a L2B-level product. At last, the retrieval model for FVC, which is neither an input nor an output variable of SCOPE, is based on field data and yields rather good performances (R^2: 0.92; relative RMSE: 18.3%). These results show that the retrieval models for the traditional biophysical variables are already quite robust in their first version. These models have been integrated in the L2D module of the FLEX Level 2 project, which streamlines the processing of OLCI and FLORIS Level 1 data until florescence retrieval and the retrieval of vegetation variables. Finally, the OLCI models have been successfully tested on real Sentinel-3 images.

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Global sensitivity analysis of coupled SCOPE-6S model.

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We quantified the relative importance of different Sentinel-3 bands for retrieval of plant traits and atmospheric composition parameters by coupling a land surface (SCOPE [1]) and an atmospheric radiative transfer model (S6 [2,3]). For this purpose, we simulated top of atmosphere (TOA) radiance of the two instruments on-board of Sentinel-3 (Ocean and Land Colour Instrument, OLCI and Sea and Land Surface Temperature Radiometer, SLSTR), and carried out a sensitivity analysis of these radiances to vegetation, soil and atmospheric parameters. The SCOPE model parameters included in the sensitivity analysis were leaf traits (chlorophylls, Cab; carotenoids, Cca; anthocyanins, Cant; water thickness, Cw; dry matter content, Cdm; senescent material, Cs; leaf mesophyll structure parameter, N), canopy traits (leaf area index, LAI; leaf inclination distribution functions parameters, LIDFa, LIDFb) and soil traits (brightness, B; soil moisture content, SMC). Top of canopy reflectance simulated with SCOPE was propagated through the atmosphere to produce TOA radiance. The atmospheric propagation was carried out with 6S using a “Continental” aerosol distribution profile scaled to provided aerosol optical thickness values (AOT). Water and ozone values were used to scale “us standard 62” atmospheric profile. Three parameters of 6S model (AOT, water and ozone) were used in the sensitivity analysis. TOA radiance values were integrated with the sensor response functions of OLCI and SLSTR. The global sensitivity analysis was done against 15 parameters with Saltelli sampling and Sobol method.

The results demonstrated that LAI and soil brightness had high impact on all the bands of both OLCI and SLSTR instruments. As expected, chlorophyll content significantly influenced bands Oa06-11 (561-709 nm) and S1-2 (554, 659 nm) and water content (both leaf and atmospheric) Oa20-21 (941, 1025 nm) and S4-6 (1375, 1613, 2256 nm). Bands beyond 750 nm were sensitive to dry matter content. The rest of the parameters showed low impact on TOA radiance with total sensitivity index close to 0.05, whereas N parameter did not demonstrate its importance at all. The next step in the analysis will be the inclusion of the SLSTR bands in the thermal domain S7-9 (3.7, 10.8, 12.0 um). The results will be used for the development of a retrieval algorithm of land surface properties from Sentinel-3.

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Modelling approaches across spatial and temporal scales I

Investigating diurnal change in spectral reflectance and solar-induced fluorescence to understand non photochemical activity (NPQ) of Arabidopsis npq mutants

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Photochemical and non-photochemical energy dissipation in plants co-occur simultaneously to balance the use of absorbed light energy between photosynthesis and photoprotection. This energy balance is even more important during high light and fluctuating light conditions. While the photochemical and non-photochemical contributions to fluorescence quenching can be resolved using active methods of measuring chlorophyll fluorescence, passively retrieved sun-induced fluorescence (SIF) cannot discriminate these energy traps. If we are to quantify plant productivity using SIF, as envisioned in Fluorescence Explorer (FLEX) mission, it is important to understand the changes in spectral reflectance and SIF that can be attributed to photochemical and non-photochemical activity. In this study, we investigated the effect of reduced NPQ capacity on SIFyield and spectral reflectance by measuring diurnally Arabidopsis thaliana mutants, one being deficient in zeaxanthin (npq1) and one lacking PsbS protein (npq4), the two components which are essential for NPQ in land plants. We observed a similar increase in SIFyield for both npq mutants compared to wildtype (WT) despite a difference in functional NPQ mechanism. Simultaneous active and passive fluorescence measurements were conducted diurnally to understand the photochemical and non-photochemical contribution in SIFyield. We extended this investigation by comparing the diurnal measurements in summer and winter to examine the effect of photoinhibition (qI) caused by low temperature. In summer, we observed higher SIFyield from morning to midday in both npq mutants as compared to the WT. At the end of the day, SIFyield of WT recovered from midday depression and the values were higher than the first measurement done in the morning, indicating a functional photoprotective mechanism for Photosystem II (PSII) activity. On the other hand, both npq mutants showed a decreased SIFyield at the end of the day compared to the first-morning reading while PSII operating efficiency (Fq'/Fm') were also reduced compared to WT suggesting damaged PSII activity due to reduced photoprotective capacity. The decline in SIFyield observed in npq mutants during summer is more pronounced in all plant types diurnally measured during winter. This decline is attributed to the development of photoinhibition, as confirmed by the decline of Fq'/Fm' and reduced recovery of maximum PSII efficiency (Fv/Fm). Cluster analysis of spectral reflectance data (in 400-750 nm range) obtained in the summer correctly separated npq1 from both WT and npq4. This led to the conclusion that spectral reflectance can resolve zeaxanthin accumulation, which is correlated to zeaxanthin-related NPQ in some conditions, but not PsbS-related NPQ. Closer inspection of spectral reflectance data revealed changes in reflectance peaking at 520 nm which can be attributed to the xanthophyll cycle, and in addition, other spectral features which cannot be attributable to changes in the xanthophyll-cycle pigments but instead ascribed to temporal change during the day. The latter included peaks at 553 nm, 630 nm and 700 nm which were consistently increasing towards the end of the day in all plants. This observation is important in accounting NPQ contribution in dynamic changes of SIF signal and spectral reflectance. Additionally, the results showed may provide additional insights for the temporal sampling of FLEX mission to observe fluorescence of terrestrial vegetation.

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Downscaling of the solar-induced chlorophyll fluorescence from canopy level to leaf/photosystem level

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Solar-induced chlorophyll fluorescence (SIF), an electromagnetic signal that can potentially indicate vegetation photosynthetic activity, can be retrieved from ground-based, airborne and satellite measurements. However, due to the scattering and re-absorption effects inside the leaves and canopy, SIF measured at the canopy level is only a small part of the total SIF emission at the photosystem level. Therefore, a downscaling mechanism of SIF from the canopy level to the photosystem level is important for better understanding the relationship between SIF and the vegetation gross primary production (GPP). Using a simple parameterization model based on the spectral invariant theory, we found that the probability for SIF photons to escape from the canopy was related to the anisotropic spectral reflectance, canopy interception of the upward solar radiation, and leaf absorption. An empirical approach based on machine learning was applied to downscale SIF constrained by the red, red-edge and far-red anisotropic reflectance, based on a training dataset generated by the SCOPE model, ground-based, airborne, and satellite observations were used to test the performance of the SIF downscaling approach. Results show that retrieved total SIF at the photosystem level matches well with simulated reference data, and the relationship between SIF and photosynthetically active radiation absorbed by chlorophyll is obviously improved by SIF downscaling. These results in combination with other evaluation criteria suggests the downscaling of canopy SIF as an efficient strategy to normalize species dependent effects of canopy structure and varying solar-view geometries.

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Sensitivity analyses of forest canopy chlorophyll fluorescence using TLS-reconstructed stands in DART

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The signal of solar-induced fluorescence (SIF) estimated with various satellite sensors has improved modelling of vegetation gross primary production at the global scale. Yet, remotely sensed SIF retrieved for forested biomes, such as tropical and boreal forests, were reported to be systematically lower in comparison to spatially homogeneous vegetations types, e.g. agricultural crops. Evidently, interpretation of forest SIF observations requires further understanding of the SIF interactions within structurally complex and heterogeneous forest canopies. With this motivation in mind, the three-dimensional (3D) discrete anisotropic radiative transfer (DART) model was enabled to simulate and upscale the chlorophyll fluorescence emissions from single leaves up to complex plant (forest) canopies. DART calculates the radiative budget and simulated air- and space-borne images of various Earth surface elements from visible to thermal infrared wavelengths at various spatial and spectral resolutions. It uses virtual 3D plants that are represented by leaves, branches and trunks built out of triangular facets. Plant 3D representations of different structural and optical attributes are distributed within a 3D scene to produce natural variability of vegetation canopies in terms of biochemistry, leaf area index, leaf angular distribution, clumping of canopy elements, and canopy closure. This ensures a rigorous simulation of photon interactions, i.e. reflected sunlight and emitted fluorescence, within the objects a given 3D scene. Coupling with the FLUSPECT leaf radiative transfer model enabled DART to simulate top-of-canopy and within-atmosphere solar-induced chlorophyll fluorescence (SIF, 640-850 nm), accounting also for scattering and reabsorption by non-photosynthetically active components such as wood.

Recent advances in high-performance computer systems and exploitation of high-density terrestrial laser scanning (TLS) data allowed for modelling of more realistic 3D virtual forest scenes. Taking advantage of these resources, we have created 3D computer representations of architecturally highly complex coniferous Norway spruce (Picea abies) and broadleaf Australian White peppermint (Eucalyptus pulchella), retaining realistic and biologically correct foliage and wood distributions. To evaluate the effects of canopy structures on SIF emissions and reabsorption, we simulated different DART scenarios where only one component of the 3D tree representations was changed at the time. Results of all scenarios were cross-compared to identify the key drivers modulating the top-of-canopy SIF peaks at 687 and 740 nm. We investigated the potential influence of wood elements (trunks and branches with various barks), the impact of foliage density and canopy clumping under a constant forest stand LAI, changes in SIF triggered by different optical properties of spruce shoot twigs, and other aspects of the forested scenes. DART results indicate a significant sensitivity of the forest canopy SIF to woody components. Presence of trunks and branches in P. abies stands decreased canopy SIF by 15% and 32% at 687 and 740 nm, respectively. A decrease in the canopy closure, i.e. clumping trees while keeping the total stand LAI of 2, lowered SIF of the E. pulchella stand at 740 nm by 35%. The presence of woody components decreased SIF at 740 nm by 24% in dense and 14% in sparse Eucalyptus forest. 17% and 10% of these declines were due to shadowing from woody structures that lowered the fraction of photosynthetically active radiation absorbed by leaves (fAPAR), while 7% and 4% of SIF emissions were absorbed by bark. By contrast, replacement of the spruce needle-twig bark optical properties by the reflectance of green needles increased the red and the far-red canopy SIF values by 12% and 24%, respectively. These sensitivity analyses demonstrated that DART simulations of the detailed TLS-reconstructed forest stands can provide unique insights regarding the sensitivity of top-of-canopy SIF to various forest structural and spectral properties, which would be difficult to unambiguously identify via experimental measurements.

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Modelling approaches across spatial and temporal scales II

Assimilating satellite SIF into a process-based terrestrial biosphere model: BETHY-SCOPE

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Satellite measurements of solar-induced chlorophyll fluorescence (SIF) offer an unprecedented insight into photosynthesis across spatial scales. The development of frameworks that utilise SIF to improve models of the terrestrial biosphere is critical to maximising the benefit of these measurements. Here we will present a data assimilation framework for SIF using the process-based model BETHY-SCOPE. Results from the assimilation of SIF from the Orbiting Carbon Observatory 2 will be presented. These SIF measurements are utilised to estimate biophysical parameters and gross primary production (GPP). With this, strong uncertainty reductions are found for biophysical parameters and GPP. Additionally, the assimilation results in large shifts in the global distribution of GPP. We will highlight the strengths and weaknesses of this framework and show how this may be expanded to include other satellite SIF products such as FLEX.

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Towards exploiting the carbon constellation of satellite missions: Using a variational data assimilation approach for a synergistic multi-mission retrieval of bio- and geophysical variables from Sentinel-1 and Sentinel-2 data.

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The potential synergies offered by the complementary use of FLEX, BIOMASS, S1, S2, S3, SMOS, TerraSAR-X and other non-European missions (e.g., GEDI, NISAR) will open a unique opportunity to address the main knowledge gaps in terrestrial carbon science. Such complementary use could happen, for example, at the level of bio- and geophysical variables that are retrieval products from individual missions through joint assimilation into a comprehensive process model of the terrestrial carbon cycle, with suitable observation operators for each of these products.

Alternatively the synergy can already be exploited in the retrieval process through a multi-mission retrieval, in which a set of bio- and geophysical variables is retrieved such that (with suitable observation operators in the form of radiative transfer models) it simultaneously provides the best-possible match to observations from multiple missions at the sensor level. Such a multi-mission retrieval has the potential to avoid the ambiguities that single mission retrievals typically face (too many unknowns to be constrained by a singe mission) and to improve the temporal and spatial coverage of the retrieval products.

The ESA-funded S3 - SENTINEL SYNERGY STUDY has developed such a synergistic multi-mission retrieval system. The system combines observations from an optical sensor (Sentinel 2) with observations from an active microwave system (Sentinel 1) in a weak constraint variational data assimilation approach. The dynamical model that is needed to close the gap between the acquisitions of the satellites formalises our expectation of the temporal evolution of the land surface state. It is deliberately simple and assigned a low weight such that the retrieval algorithm has much freedom to deviate from this model. This choice ensures a high impact of the Sentinel observations on our retrieval products. Our state space contains LAI, vegetation height, and soil moisture. From these direct retrieval products we derive further retrieval products such as FAPAR and phenology. The system uses two physically consistent radiative transfer models, the semidiscrete model for the optical domain and the single scattering radiative transfer (SSRT) model for the microwave domain. There are two sets of prior information: The first one is a generic time and space independent prior and the second one is derived from simulations with the Joint UK Land Environment Simulator (JULES). The algorithm provides time varying per-pixel uncertainty estimates for each variable including the uncertainty correlation between variables.

In the study, the system is applied over an agricultural landscape. Results are validated against field measurements over the Munich-North-Isar site, Germany. The comparison with the field data demonstrates how the retrieval of bio- and geophysical variables benefits from the synergistic approach. It will be highlighted that the retrieval of soil moisture greatly benefits from the simultaneous retrieval with LAI. On the other hand, the high frequency of Sentinel 1 acquisitions improves the retrieval of an LAI time-series. Through analysis of a series of satellite unavailability scenarios we quantify the contribution of individual satellites and specific band combinations/polarisations on the uncertainty in the retrieval products and on temporal consistency.

The retrieval system is designed in a modular and flexible way in order to facilitate integration of observation operators for further missions.

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Forward modelling of Solar Induced Fluorescence from the JULES land surface model

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Solar induced fluorescence (SIF) is becoming widely used as a proxy for gross primary productivity (GPP), in particular with the advent of its measurement by Earth Observation satellites such as OCO and GOSAT. The upcoming launch of FLEX offers exciting new opportunities to understand these processes at a much finer spatial resolution.

A major attraction of SIF is that it is independent of the assumptions embedded in light use efficiency based GPP products derived from satellite missions such as MODIS. The assumptions in such products are likely not compatible with any given land surface model and hence comparing the two is problematic. On the other hand to compare land surface model predictions of GPP to satellite based SIF data requires either (a) translation of SIF into estimates of GPP, or (b) direct predictions of SIF from the land surface model itself. The former typically relies on empirical relationships, whereas the latter can make direct use of our physiological understanding of the link between photosynthesis and fluorescence at the leaf scale and is therefore preferable.

Here I use a two stream model for fluorescence that is capable of translating between leaf scale models of SIF and the canopy leaving radiance taking into account all levels of photon scattering and use it to forward model SIF observations from JULES (the Joint UK Land Environment Simulator) which is the land surface model of the new UK Earth System Model (UKESM). Other such fluorescence models have been developed previously but the model described here is physically consistent with the Sellers' two stream radiative transfer scheme which is widely used in modern land surface models. Consequently any model that already employs the Sellers's scheme can use the new model without requiring modification.

The JULES-SIF model is run at a number of sites where measurements are available. Results show that it is possible to reproduce the observed SIF signal, but that understanding the magnitude of non-photochemical quenching is key to making correct predictions.

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Fluorescence for aquatic research I-II

FLEX2018 cruise: preliminary results for the bio-optical characterization of the investigated coastal area (Tyrrhenian Sea)

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In the framework of the ESA "FLEXSense Campaign 2018" and Copernicus Marine Environmental Monitoring Service (CMEMS) project, the Global Ocean Satellite monitoring and marine ecosystem group (GOS)

of the Italian National Research Council (CNR) organized the oceanographic cruise “FLEX2018” in coastal waters of the Tyrrhenian Sea, providing a ground station for several bio-optical instruments onboard the CNR research vessel “Dallaporta”.
The GOS sampling activities were conducted in timing synergy with space (Sentinel 3A and Sentinel 3B) and airborne observations, with the intent to contribute to the calibration/validation activities for existing and future mission developments.
Here, we present the preliminary results for the bio-optical in-situ characterization of the investigated area, as a contribution to the main “FLEXSense Campaign” goal based on the atmospheric correction for the Sentinel-3 - FLEX tandem mission and to the evaluation of the “FLuORescence Imaging Spectrometer” (FLORIS) applicability to the coastal marine environment features.

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Retrieval of sun-induced fluorescence in optically complex waters: Insights from observations of the Sentinel-3 tandem phase

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Sun-induced fluorescence (SIF) from phytoplankton is recognized for its good correlation with the water quality parameter chl-a concentration and has been a widely used parameter in in-situ and laboratory measurements particularly for ecological studies. The presence of in-water constituents aside from phytoplankton, however, challenges the retrieval of sun-induced fluorescence (SIF) in optically complex waters. Further, high spectral resolution in the red-NIR region spectral is necessary to extract the full SIF emission shape in high detail and increase the accuracy of SIF retrievals, which is not available in multispectral sensors (e.g. MODIS, MERIS, Sentinel-3 OLCI). The upcoming Fluorescence Explorer (FLEX) mission currently under development by the European Space Agency provides hyperspectral capability between 500-780nm and can possibly be used to advance SIF retrievals and therefore water quality monitoring of coastal and inland waters.

This study aims to investigate different retrieval techniques for phytoplankton fluorescence in optically complex waters and their potential to distinguish different algal groups. We use a unique data set obtained between June – August 2018 in the Tyrrhenian Sea (Italy) and in the inland water site Greifensee (Switzerland). The data set comprises concurrent measurements with in situ (Fluorescence Box, FloX), airborne (HyPlant) and spaceborne (Sentinel-3A,-3B) spectrometers. We apply several retrieval methods including the fluorescence line height method, a differential absorption spectroscopy approach, and an inversion of a bio-optical model. We quantitatively assess the suitability of the retrieval methods cross observational scales to disentangle reflected from emitted fluorescence light and to compensate for atmospheric disturbances. We discuss possibilities and potential limitations of the individual retrieval strategies.

Our results and insights will guide the development of novel and robust SIF retrieval approaches for inland and coastal waters. This may also potentially lead to a water quality product for FLEX. The availability of more efficient techniques in obtaining SIF will be beneficial for water quality monitoring (e.g. harmful algal bloom detection) and will facilitate ecological studies (e.g. identification of phytoplankton functional types, primary production assessments). Finally, our results will further demonstrate the significance of FLEX mission data for aquatic research and its many applications.

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A new SICF retrieval algorithm for water bodies and the implementation possibilities for the FLEX/S3 tandem mission.

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The modelling of the spectral behaviour in bodies of water is not trivial, due to the high spectral variability of the different water compounds. Similarly, the Sun Induced Chlorophyll Fluorescence (SICF) signal produced by phytoplankton and leaving the water body is affected by these different water compounds.

To separate to the SICF emission from the peak produced by the combined effects of water and phytoplankton absorption a new retrieval algorithm was developed, as improvement to the commonly used Fluorescence Line Height (FLH) method. Here, two concepts of Remote sensing reflectance (Rrs) has been used: (1)
real water-leaving reflectance (Rrsr) corresponding to Rrs without SICF contribution and (2) water-leaving apparent reflectance (Rrsapp) corresponding to Rrs with SICF contribution. In nature, only (Rrsapp) is detectable at water surface level. Because of this, a

methodology able to separate Rrsr from Rrsapp is proposed. We estimated Rrsr based on normalized Rrsapp at 780 nm (Rrsappn780) by using spectral ranges that are not affected by the emitted SICF signal. From simulated data we observed that Rrsappn780 can be modelled as a polynomial of 8 degrees expression. Also, a strong correlation between the spectral range inside of the SICF emission signal and the both spectral ranges outside of the SICF emission signal was corroborated. Hence, by finding three adjust points inside of the SICF emission spectral range based on (1) the points outside the SICF range and (2) the Rrsappn780 polynomial. To estimate the adjust points inside of the SICF emission spectral range, Machine Learning Regression Algorithm (MLRA) methods and LookUp Table Based Inversion (LUT-BI) were used. A validation was performed using simulated data.

To corroborate the application of the newly proposed algorithm for the FLEX-Sentinel 3 mission, the simulated database was convolved to the spectral response of OLCI and both the FLH and the new algorithm were tested. The new algorithm obtained relative errors with respect to the true SICF less than 20% in 70% of the cases of SICF estimated at 685 nm and in 80% of the cases for the estimation of spectrally integrated SICF (661-710 nm). The FLH method, on the other hand, showed relative errors less than 20% only in the 11% of the cases for the estimation of spectrally integrated SICF (661-710 nm).

Additionally, the implementation requirements for the algorithm in the FLEX-Sentinel 3 mission were evaluated, considering (1) the Signal-to-Noise Ratio (SNR) of the sensor and (2) the effects of the atmospheric correction. According to this study we observed that (1) The impact of the type of atmosphere affects to the ρ wapp retrieval is low comparing to the instrumental noises effects, but is evident that in the case of a dense atmosphere the retrieved Rrsapp is noisier than in the case of a light atmosphere.

(2) The FLuORescence Imaging Spectrometer (FLORIS) SNR is enough to obtain a good signal of bodies of water, as long as the Rrsapp levels are high enough to overcome the levels of instrumental and atmospheric noise. This will depend as much on the irradiance conditions as on the composition of the water. In conclusion, the new proposed SICF retrieval shows good results under the condition a good FLEX atmospheric correction can be performed, requiring a high water body reflectance, optimal atmospheric conditions and a very accurate ISRF modelling. This research opens the door to higher precision and more exhaustive studies of the behaviour of phytoplankton and its photosynthetic activity at the local and global scale.

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Analysis of high frequency of remote sensing reflectances in optically complex waters for the next generation of hyperspectral sensors

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The complex aquatic ecosystems, such as lakes, are generally characterized by a high degree of spatial and temporal changes. In particular, hourly and daily dynamics are evident due, for examples, to the growth/decrease of phytoplankton depending on light availability and to the variation of the suspended solids in wind-induced resuspension of the bottom sediments. Such a variability is then changing depending on location, so that variation in spatial patterns is also a typical feature of these ecosystems.

Satellite images have been used widely since many decades to observe and to understand spatial and temporal variability of water constituents, while the exploration of hourly temporal variability is still limited to geostationary sensors, whose spectral and spatial resolutions are anyway limited for resolving the optically complexity of inland waters. To fill this gap, in this contribution we present the results obtained by acquiring Remote Sensing Reflectance (Rrs) from two hyperspectral spectroradiometers mounted on fixed platforms and / or on floating buoys. These sensors allow to gather continuous measurements during the day and for several consecutive days from two different yet comparable devices. A set of Rrs measures were taken by a WispStation (manufactured by Water Insight) in Lake Trasimeno (in the April-September 2018 range). The system measures every 10 minutes the radiance and irradiance in the spectral range of 350-900 nm with a spectral resolution of 3 nm. The set-up is based on an automatic system so that the instrument detect the water surface at optimal azimuth angles for most of the day. A second set of Rrs spectra was instead acquired by a ROX sensor (manufactured by JB Hyperspectral devices) operated on a floating buoy in Lake Maggiore at the end of June 2018. The ROX system is assembling Ocean Optics spectroradiometers and it operates in the range 400–950 nm with a spectral resolution of 1.5 nm and with an acquisition time of 1 minute.

Rrs data collected by both systems were pre-processed for quality control and mostly for removing glint. The noise-free data were then analysed to investigate phytoplankton types mostly in terms of Chlorophyll-a (Chl-a) concentrations, phytoplankton pigments and of Sun Induced Chl-a Fluorescence (SICF). This analysis was performed based on forwarded simulations of the radiative transfer code Hydrolight (mostly for a sensitivity analysis on SICF signal) and bio-optical modelling parameterized with the specific inherent optical properties. The inversion of Rrs data from WispStation in Lake Trasimeno showed that chl-a concentrations showed variations higher of 100% during the day. The ROX data in Lake Maggiore allowed to evaluate the presence of a small peak due to the SICF in late afternoon data.

Rrs data were then resampled based on radiometric settings of the satellite sensors that are (or will be) crucial for investigating phytoplankton properties in inland waters such as: Sentinel-3A OLCI, Sentinel-3B (with the OLCI sensor working in 'FLEX modality' with about 50 bands, rather than 21), FLEX and PRISMA hyperspectral missions. The analysis aims to adapt the state-of-the art algorithms for retrieving biogeochemical parameters to the next generation of hyperspectral satellite (apart a continuous testing with OLCI).

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Modelling Environmental Impacts And Adaptation On Sustainable Marine Ecosystems In the Gulf-of-Guinea Coast

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The global climate change influence marine animals through the ocean warming, acidification and oxygenation. This has affected the socioeconomic aspect of acquaculture through changes in seawater chemistry, sediment transport, decrease in seawater pH (acidification) etc. The study was conducted in the Gulf of Guinea region of the North Atlantic which stretches from the Senegal in the West to Gabon to the South-Eastern part of Africa. It is home to a large number people and economic activities with over fifty (50) million African population. In order to ensure the preservation of preserving natural resources and marine ecological features, a modified methodological approached was developed to evaluate risk of marine ecosystem.

Monthly annual sea surface temperature data were obtained the National Oceanic and Atmospheric Administration (NOAA) and Advanced very-high-resolution radiometer (AVHRR) over the Gulf-of-Guinea region between 1972 to 2017 (45 years) were analysed in relation to acess the long term trend of ocean heat transport and changes in ocean circulations within the study area High resolution Sentinel-2, ALOS PALSAR and ASTER satellite images were acquired and processed coastal vegetation, erosion assessments, extract emissivity and temperature and spatial modelling, that are in combination with historical estuary evolution and field observation was applied for effective management and conservation the ecosystem features of the area. It was then observed that the climate change impacts on aquaculture is highly predominant in tropical and subtropical climatic regions of the world, thus there is need to assess the implications of future scenarios in terms of climate change and research development in the areas of aquaculture. The recommendations from this research thus improve strategies and policy measures needed to fight the observable and projected climate change impacts on fisheries and aquaculture, so as to protect the livelihoods of the fishing communities and food security. Finally, Integrating the needs of fish farmers and acquaculturists into adaptation planning is very essential.

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In situ measurement of fluorescence II

Ground-based fluorescence measurements and vegetation dynamics across different ecosystems

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In this contribution, we present activities and ground-based results obtained in recent campaigns conducted in the context of the future spaceborne FLuorescence EXplorer (FLEX) mission. In summer 2018 several test sites, encompassing agricultural and forest ecosystems, were investigated at field, airborne and satellite level to demonstrate the feasibility of fluorescence retrievals for a better understanding of the functioning of vegetation from space.

All sites were equipped to acquire in situ measurements of top of canopy radiance, atmospheric properties and eddy covariance measurements. Reflectance and sun-induced fluorescence at ground level were estimated starting from spectral data collected with the FloX system, to get both continuous time series across full vegetative periods and to characterize the spatial representativeness of the sites. At the Italian agricultural site, we sampled different crops from February 20th up to 15th September to collect biophysical vegetation parameters and solar induced fluorescence in different phenological conditions and with different irrigation scheme. We particularly present the results for the retrieval of the full fluorescence spectra and the evaluation of different fluorescence metrics, towards FLEX Level 2 products, for better interpreting time courses and spatial pattern dynamics of fluorescence of the investigated land use and cover. Ground-based spectrometers and the establishment of an international fluorescence network can offer several benefits toward a better understanding of terrestrial ecosystems, an improvement of operational atmospheric corrections, and provide necessary information for the calibration/validation of multi-source remote sensing data and products.

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Chlorophyll Fluorescence Calibration/Validation Measurements at the USDA Beltsville research cornfield over 20 years

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This presentation will summarize the evolution of field and laboratory measurements that comprise our proximal sensing protocols for fluorescence and plant biophysical parameters (e.g., maximum photosynthesis, chlorophyll content) at the USDA research site in Beltsville, MD, USA. The methods and measurements we made over the past two decades evolved for collecting consistent leaf and canopy measurements for corn (maize) crops in different years and with different soil nitrogen augmentation levels. We also highlight results from one summer season when we tracked canopy responses during a drought for corn stands provided both water and nitrogen treatments. We describe the development of a 10 m tower system for our custom multi-instrument and multi-angle optical system, FUSION, to survey the canopy along with an eddy covariance tower to track the carbon dynamics. In the past two years, we added a D-FloX system and complementary in-situ leaf-level measurements from a MONItoring Pulse Amplitude Modulated (Moni-PAM) system, supplemented by spectrally resolved FluoWat collections. We provide both diurnal and seasonal trends for red and far-red solar-induced fluorescence (SIF) and reflectance indices (e.g., PRI, NDVI), and demonstrate how we used our combined measurements as input to the SCOPE model to estimate light use efficiency and gross primary production.

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Effect of the canopy architecture on the diurnal time course of sun-induced chlorophyll fluorescence and derived indices

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Remote sensing of sun-induced fluorescence (SIF) from terrestrial vegetation is the subject of intense research, with the aim to evaluate photosynthetic efficiency at large scales under various environmental conditions. The FLEX mission is specifically designed for SIF measurements and will provide fluorescence products from space at an unprecedented spatial and temporal resolution. Indeed, chlorophyll fluorescence (ChlF) emission is tightly linked to the photosynthetic mechanisms as it emanates from the energy absorbed by photosynthetic pigments and competes with photochemical conversion. Under various stress conditions, acclimation of plants results in an increased dissipation pathway (i.e. non photochemical quenching) that affects the stationary ChlF yield under ambient light. Active measurements of ChlF diurnal cycle at leaf or canopy level showed a significant decrease of the fluorescence level in the middle of the day upon water stress, compared to control conditions. However, the diurnal cycle of SIF also includes the absorbed photosynthetically active radiation (APAR), which results in the complex interaction of incoming sun radiation and canopy architecture. The radiative transfer of fluorescence in the canopy should also be taken into account. In this study, we investigate the effect of canopy architecture on the diurnal cycle of SIF using a modeling scheme coupling Modtran 4, FluorMODleaf and SAIL. Different normalization procedures are evaluated according to canopy structure parameters (leaf area index, leaf angular distribution, chlorophyll content), with the aim to discriminate between water stressed plants and control and we propose a new fluorescence-based index for water stress detection.

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Correcting for Sun Induced Fluorescence reabsorption – from leaf to canopy – in chlorophyll-deficient and green soybean plants

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Novel measurement techniques to estimate sun-induced chlorophyll fluorescence (F) together with the hyperspectral reflectance (R) have become available in recent years. A relevant question is whether the combined use of these measurement techniques can help to quantify the productivity of different crop varieties. We investigated the F and R of two varieties of Soybean (Glycine max (L.) Merr.), a chlorophyll-deficient (MinnGold, chlorophyll (Cab) of 9.52±0.98 mg cm-2) and a non-chlorophyll deficient (Eiko, Cab of 46.49±5.59 mg cm-2) variety, in order to explain similarities and differences in photosynthesis and light use efficiencies. We were particularly interested in explaining the light absorption and fluorescence emission at photosystem level, which are both indicators of photosynthesis.

Our measurements of top of canopy (TOC) F and R, and canopy level gross primary productivity (gas exchange chambers) showed that despite the higher Cab of the Eiko both varieties present similar canopy-scale gross primary production, and the ratio of carbon uptake to light absorption ratio was higher in the MinnGold. We further retrieved parameters for the 'Soil-Canopy-Observation of Photosynthesis and Energy fluxes' model (SCOPE) from leaf and (TOC R, and used SCOPE to correct F for reabsorption of fluorescence in the canopy. The emission of fluorescence in the photosystems appeared to be similar in both varieties. This indicates that the higher light absorption in the Eiko as compared to the MinnGold is compensated by higher non-photochemical quenching (NPQ) due to light saturation. Our findings demonstrate that the combination of F and hyperspectral R can help better understand and quantify the light reactions of photosynthesis in crop varieties.

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Linking fluorescence and ecosystem processes I - water cycle

The relationship between sun-induced fluorescence and transpiration is determined by atmospheric conditions and less by vegetation properties

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Satellite observations have revealed that relationships between sun-induced fluorescence (SIF) and latent heat flux (lE) are at least as strong as those between SIF and GPP. This could provide a new means to estimate transpiration more directly and accurately from space. In this research, we used the Soil Canopy Observation of Photosynthesis and Energy fluxes (SCOPE) model to better understand the drivers of the relationship between SIF and lE. We calibrated SCOPE for each available day of each individual site of the FLUXNET2015 database, using MODIS data and eddy covariance observations of GPP and lE and calculated SIF. This yielded a dataset of over 50k realistic simulations of 10 different biomes. Whereas the SIF-GPP relationship was, as expected, mostly influenced by vegetation properties, the SIF-lE relationship was hardly influenced by these vegetation properties, including even carbon metabolism, but was largely determined by atmospheric conditions, i.e. net radiation, air temperature and vapour pressure deficit. This facilitates a more direct estimation of transpiration over large scales, making use of upcoming advances in satellite SIF.

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Tomography of forest gas exchange: Implications for the development of novel FLEX mission data products

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Comprehensive assessments of functional, biochemical and structural plant traits is pivotal to assess the status of plants and reveal subtle interactions and feedbacks between environmental forces and ecosystem functioning. Established active and passive remote sensing approaches (e.g. using Sentinel-1, -2 and -3 mission data) provide a diverse set of information on plant's biochemistry and structure. The development of European Space Agency's upcoming Fluorescence Explorer (FLEX) mission will complement existing observational capability and, for the first time, allow assessing functional traits representing actual plant mediated gas exchange processes (i.e. net CO2 assimilation (A), transpiration (T)).

The development of FLEX mission data products representing plant's gas exchange requires combining remote sensing measurements with established in situ observations of gas exchange (e.g. eddy covariance (EC) measurements). Combining both observational approaches, however, is an unsolved scientific problem and caused by fundamentally different sampling strategies of both techniques. While EC measurements represent a spatially varying area of a vertically integrated canopy, remote sensing measurements represent the upper leave layer of a fixed canopy region. Further, the relation of both observations varies in time and space depending on how the upper canopy layer is coupled with or decoupled from the vertically integrated canopy.

In this study, we provide a tomographic perspective on the gas exchange of a forest canopy. We use 3D radiative transfer models, ecohydrological models, in-situ fluorescence measurements and micrometeorological observations (including EC measurements) to simulate 3D fields of transpiration T and A. We analyze these 3D fields to quantify the relation of T and A from the upper canopy (remote sensing perspective) with the vertically integrated T and A (EC perspective). We assess the impact of canopy structure and environmental conditions on observed relationships. We identify strategies to compensate for a possible footprint mismatch and to account for the "remote sensing bias" when assessing 3D forest canopies. Our findings provide substantial insights to facilitate the harmonization of remote sensing and in situ gas exchange measurements. Results will guide the definition of novel FLEX mission data products and of optimal validation strategies for such products.

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Investigating the potential of sun-induced chlorophyll fluorescence to advance estimates of ecosystem transpiration

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Transpiration (Tr) is an important and complex plant physiological process in terrestrial ecosystems and significantly impacts the global water and energy balance. Assessing the dynamics of Tr has versatile implications to understand causes of water scarcity, to advance the understanding of interactions and feedbacks between global climate change and ecosystem functioning, to assess plant water use efficiency for optimized agricultural management, and to exploit the coupled carbon and water cycle. Nevertheless, spatio-temporal assessments of Tr using models or Earth observation (EO) informed approaches are still uncertain due to the complexity of Tr, limitations in existing methodology, and lack of observational approaches only accounting for potential rather than actual Tr. New pathways arise from the development of ESA's upcoming Earth Explorer mission Fluorescence Explorer (FLEX), which will provide global measurements of sun-induced chlorophyll fluorescence (SIF). SIF is considered the most direct measurement of plant photosynthesis and possibly allows informing approaches to estimate actual Tr.

In this study, we assess a possible contribution of SIF to advance cross scale Tr by comparing estimates of potential and actual Tr and its dynamics under the extremely warm and dry 2018 summer in Europe. We apply a mechanistic approach combining process modeling (i.e. a combination of the Penman-Monteith (PM) and the Ball-Berry-Leuning (BBL) model) and multi-source EO data (i.e. Sentinel-3, European Centre for Medium-Range Weather Forecasts (ECMWF)) to calculate actual and potential Tr. In particular, we varied the parameterization of the canopy surface resistance with a greenness based estimate of photosynthesis (potential Tr) and a SIF surrogate (actual Tr). Estimates of potential and actual Tr were validated with flux data from eddy covariance sites in Europe. Further, we quantify dynamics of Tr under different climatic conditions using monthly time series of selected study sites in southwestern Europe over two years, the drought year 2018 and the baseline year 2017.

Our results reveal complex patterns of Tr dynamics (potential and actual) over two years in Europe. We discuss these results considering possible superimposing environmental factors for different ecosystem types. Obtained insights show the possible contribution of SIF and the need of additional environmental factors for reliable estimates of actual Tr from regional to global scale. Our study is important for the definition of higher level FLEX mission products facilitating estimates of Tr dynamics in space and time.

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The mechanistic link between transpiration and sun-induced chlorophyll fluorescence in a mixed forest: Insights from the 2018 European drought

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Plant transpiration (T) accounts for 60 to 80% of terrestrial evapotranspiration, thereby having a dominant influence on the global water cycle. As temperatures increase and more extreme droughts are expected to occur, it is unclear in which direction T will evolve in our ecosystems; T could, for example, decrease due to stomatal closure leading to an increased warming or T could be stimulated by the increased ability of the atmosphere to hold more water vapour leading to a cooling effect. In order to understand these vegetation response dynamics and inform models, measurements are needed at ecosystem-level to quantify the evolution in T. However, consistent T measurements at ecosystem-level are currently lacking. The mechanistic linkage between photosynthesis and T by stomatal conductance opens new possibilities to inform T estimates by sun-induced chlorophyll fluorescence (SIF), the most direct remote sensing measurement of plant photosynthesis.

In this study, we apply a novel approach using concurrent below and above canopy eddy covariance (EC) measurements in a mixed deciduous forest in Switzerland to partition water vapour fluxes into evaporation and T, based on the coupling of the layers and on the origin of the water vapour sources. We then explore the mechanistic link between the T-derived and SIF retrieved from continuous tower-based FloX measurements, as well as their link to stomatal conductance, water stress, and other environmental factors. We found that, in our mixed forest, mid-afternoon reductions in T occurred during periods of high vapour pressure deficit in summer. T and SIF similarly declined during the drought of the 2018 summer, due to the water stress imposed on the trees. Our results contribute to a better understanding of T dynamics during drought conditions as well as their link to SIF. Provided insights will guide further developments of SIF informed modelling approaches to estimate T across spatial scales.

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Linking fluorescence and ecosystem processes II - carbon cycle

Mechanistic processes driving Sun-Induced Fluorescence and Gross Primary Production under nutrient manipulation

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Sun induced fluorescence (SIF), the radiation flux emitted by plant chlorophylls molecules in the 650-800 nm spectral window, is considered an indicator of photosynthetic performance. Recently it has been shown that SIF can track changes in light use efficiency (LUE), and therefore it is a good predictor of gross primary productivity (GPP) at various scales, from leaves and ecosystem to regional and global scale.

Although SIF has been successfully used to predict GPP in various ecosystems, the mechanistic link between GPP and SIF remains not fully understood, and especially the effect of functional and structural traits on SIF at the canopy scale remains an active area of research.

SIF is emitted by the whole canopy, but only a fraction of the total emission is observed with remote sensing techniques. The escape probability of SIF (Fesc) controls the amount of SIF scattered by the canopy and is integral to separate the effect of canopy structure and function on the fluorescence signal.

Approaches based on the LUE equation are widely used to model the relationship between GPP and SIF, however a lack of process understanding as well as difficulties in parametrization of the LUE terms; light use efficiency of photosynthesis (LUEp) and efficiency of fluorescence emission (LUEf), as well as Fesc, limits the applicability of this method.

In this contribution we make use of data collected at the research site Majadas de Tietar, a Mediterranean grassland manipulated with nitrogen and phosphorus. With a combination of processes-based soil-vegetation-atmosphere transfer modelling (SCOPE model) and data driven analysis (relative importance analysis, and path analysis with intervention), we unravel the processes and causal relationship that are at the base of the GPP-SIF relationship. Additionally, via path analysis we understand how different nutrient conditions alter the mechanistic processes that drive both GPP and SIF.

We show that functional traits such as leaf nitrogen content influence SIF emission and GPP in a rather indirect way, being the nitrogen effect on SIF emission mainly mediated by absorbed photosynthetic active radiation (APAR) and surface temperature. On the other hand, structural variables affect SIF emission by modulating APAR and influencing SIF by varying Fesc.

As the GPP-SIF relationship across nutrient treatment shows significant changes on N fertilized plot, we show which are the main drivers and the most important processes that mechanistically influence the relationship. In particular in the first year of fertilization, changes in GPP-SIF were mediated by a combination of functional and structural variability, whereas in the second year, changes in plant functional type abundances cause a strong structural variation that in turn influences SIF by means of higher APAR and Fesc.

This contribution advances the knowledge of the highly complex dynamics involved in the GPP-SIF relationship. In depth understanding of the mechanistic processes is required to fully take advantage of the increasingly prevalent SIF data streams

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Partitioning the structure and photosynthetic pathway for scaling solar-induced fluorescence to gross primary production from satellite observations

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Photosynthesis by terrestrial vegetation absorbs half of anthropogenic CO2 from the atmosphere. Large-scale photosynthesis quantification has remained challenged due to the lack of sufficiently accurate remote sensing proxies. It is therefore critical to accurately measure photosynthesis at the spatial scale of ecosystem to global. Remote sensing of sun-induced chlorophyll fluorescence (SIF) has been shown a good indicator of vegetation photosynthesis or gross primary production (GPP) across diverse scales. Along with the breakthroughs of global retrievals of SIF from space-borne sensors, exploitation of SIF in improving the estimation of terrestrial GPP became a very relevant and active field. However, it remains unclear how the slopes of GPP-SIF relationship vary across biomes due to canopy structure and physiological factors due to photosynthetic pathway, especially as a result of lacking long-term field measurements of SIF and scale mismatch between satellite SIF data and flux tower GPP estimates. In this presentation, we present a synthesis of field continuous measurements of SIF across biomes which is used to unravel the GPP-SIF relationships across different biomes together with improved SIF retrievals from OCO-2. We find that the slopes of raw SIF with respect to GPP are significant different among biomes, which we attributed both to canopy structural effects as well as to differences in photosynthetic strategies. After accounting for the escape effects from canopy structure with the corresponding BRF, however, a photosynthetic-pathway dependent GPP model from SIF emerges for C3 and C4 plants that allows for simple calculation for terrestrial photosynthesis at the global scale. This results are supported by process-based model simulations. With the new GPP models from adjusted SIF with the corresponding NIR BRF for C3 and C4 plants, fully observation-based and independent global GPP estimates (126.80±1.22 PgC/year) are derived for the period of 2015-2017 from OCO-2 SIF retrievals; this falls within the range of current terrestrial biosphere models and up-scaled flux tower estimates. Our results indicate that the slopes of GPP-SIF relationship across biomes are jointly controlled by canopy structure and physiological factors, and a photosynthetic-pathway dependent SIF-based GPP model provide a simple and independent constraint on terrestrial photosynthesis at the global scale.

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Improvements in GPP spatio-temporal patterns simulated with the ORCHIDEE terrestrial biosphere model resulting from the assimilation of OCO-2 solar-induced fluorescence products and the development of a mechanistic SIF model

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By offsetting about one fourth of carbon dioxide (CO2) emissions released by anthropogenic activities into the atmosphere, terrestrial ecosystems plays a pivotal role for climate. The assimilation of CO2 by photosynthesis that occurs in leaf chloroplasts is largely compensated by ecosystem respiration and fires that release some of the CO2 back into the atmosphere. As highlighted by the large spread in dynamic global vegetation model (DVGM) simulations relative to the spatio-temporal patterns of the terrestrial gross primary productivity (GPP), large uncertainties remain in our understanding of the carbon sequestration in land surfaces. Part of these uncertainties result from unknown or poorly calibrated parameters in DGVMs. Over the past decade, the use of space-borne retrievals of solar-induced fluorescence (SIF) as a proxy of GPP at large temporal and spatial scales has grown in importance. Their use for constraining DGVMs implies that these models are able to simulate SIF observables and represent the functional links between GPP and SIF.

In this study, we present the development of a SIF observation operator in the ORCHIDEE DGVM (Krinner et al., 2005). It relies 1) on a novel parameterization of NPQ as a function of temperature, APAR and the normalized quantum yield of photochemistry (i.e. ratioed by the maximum quantum yield of photochemistry), to simulate the regulation of the PSII fluorescence quantum yield at the leaf level, and 2) a parametric simplification of the SCOPE model to emulate the radiative transfer of chlorophyll fluorescence to the top of the canopy.

We then apply a Bayesian assimilation framework to assimilate monthly OCO-2-SIF product at 0.5° over the period 2015-2016 and hence calibrate ORCHIDEE over an ensemble of pixels for all vegetation plant functional types (PFTs). Through the optimization of photosynthesis and phenological ORCHIDEE parameters mostly, the feedback on the simulated GPP is considerable with a decrease of the global budget by 33 GtC.yr-1 over the 1990-2009 period (from 162

GtC.yr-1 with the standard model parameters to 129 GtC.yr-1 after assimilation). Although the optimized global GPP budget gets in close agreement with that of independent FLUXCOM GPP products (Tramontana et al., 2016) (121 GtC.yr-1 in average over the same period), the spatio-temporal distribution of the improvement of ORCHIDEE relative to both OCO-2-SIF observations and FLUXCOM-GPP estimates show contrasted results between ecosystems. Indeed, our assimilation framework results in opposite variations in the modeled SIF and GPP for temperate and boreal deciduous forests, contrary to other PFTs. This suggest a biome dependency of the SIF-GPP relationship, likely through differences in the radiative transfer regime, that needs to be resolve to enhance the observational constraint brought by space-borne SIF products on vegetation productivity. We discuss the benefits of using SIF data to constrain DGVMs with regards to other available observations.

Linking fluorescence and ecosystem processes III

Sun-induced chlorophyll fluorescence to understand the responses of terrestrial ecosystem functioning to climate, environmental changes and extreme events

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Understanding the responses of ecosystem functioning to climate extremes and environmental changes is an imperative question in global change ecology. Therefore, the development of tools for monitoring the effects of increasing temperature, water stress, increasing atmospheric CO2 concentration, and nutrient availability on ecosystem functioning (e.g. photosynthesis and water use efficiency) is pivotal. Reflectance based spectroscopy can be used to directly infer variations in biochemical and partially structural changes of vegetation under different meteorological and environmental conditions. Besides, novel measurements of sun-induced chlorophyll fluorescence (SIF) both in the red and far-red regions open new pathways to non-invasively quantify dynamic changes in ecosystem functioning. However, the mechanistic link between photosynthesis, water use efficiency and SIF under different environmental conditions is not completely understood yet.

In this contribution we will synthesize the information coming from a series of campaigns at different eddy covariance sites as well as climate and nutrient manipulation experiments. We collected data from 1) a nitrogen (N) and phosphorous (P) manipulation in a Mediterranean grassland; 2) and a climate manipulation experiment, with elevated CO2 (+0, +300 ppm), temperature (+0, + 3 ºC) and water stress (rain manipulation with shelters), and the combination of the three factors; 3) and various sites where eddy covariance data and SIF were measured simultaneously. These sites include a Mediterranean tree grass ecosystem with different nutrient availability, a semi-arid pine forest, and an orchard. The sites experienced a series of drought events and/or a heat wave. The common set-up in all sites is the combined measurement of CO2, Net Ecosystem Exchange (NEE) with subsequent partitioning of Gross Primary Productivity (GPP), and evapotranspiration fluxes (either with chambers or with eddy covariance technique) with SIF in the O2-A (~760 nm) and O2-B (~687 nm) absorption features (obtained from the Fluorescence BOX, JB Hyperspectral Devices). Occasionally, the dataset is complemented by in situ measured leaf traits such as nutrient content, vegetation pigments and leaf area index (LAI) measurements, maximum carboxylation rate (VCmax) and maximum photosynthesis rate derived from leaf A-Ci curves, sap-flow measurements, carbonyl sulfide measurements (OCS), and leaf isotopes signature measurements (in particular δ13C). A model data integration approach combining simulations performed with the SCOPE model with the collected data was used for process understanding.

Results show that elevated CO2 causes an increase of both GPP and SIF. SCOPE simulations show that the increase in SIF emission can be explained by the reduction of Non Photochemical Quenching (NPQ) associated with the higher observed VCmax and intercellular CO2 concentration (Ci), which ultimately leads to higher SIF than under ambient CO2. The N fertilization induced changes in canopy structure (i.e.

changes in plant form abundances that influence leaf inclination distribution function) and functional traits (e.g. nitrogen content per dry mass of leaves, Chlorophyll ab concentration, VCmax), which lead to an increase of SIF and GPP, but with a functional relationship between the two variables and modulated mainly by community structure (e.g. fraction of graminoids) and secondarily Vcmax. Surprisingly, we observed a statistical significant effect of P on SIF emission that we demonstrated to be related to the enhancement of the electron transport rate associate with higher P content in leaves. GPP and SIF under water stress treatments and combined CO2, temperature stress, and water stress showed the expected reduction, associated with an increase in water use efficiency. This comprehensive dataset shows that changes in species and therefore structure and leaf contents induced by treatments can enhance SIF sensitivity to vegetation responses, but have also a confounding effect on the connection between SIF and functioning. Integrated approaches capable of characterize plant structure, composition and function together are necessary to truly understand the different strategies of vegetation to face environmental change. Less clear is the effect of heat waves and temperature stress: while we overall observed reduction of GPP, the response of SIF and water use efficiency is very different across vegetation types. We hypothesize that this response might be related to different stomatal behavior and strategies to cope with heat stress (and in particular stomatal vs non stomatal regulation of photosynthesis), variations in the capacity of the vegetation to recover from high night-time temperature, or that the temperature increase was not enough to stress the vegetation and go beyond the optimal temperature.

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Estimating functional diversity using sun-induced fluorescence in terrestrial ecosystems

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Biodiversity plays an important role in ecosystem functioning by promoting a wide range of functions and services. Functional diversity is a component of biodiversity, which describes the variability of those plant traits that influence ecosystem functioning. Changes in functional diversity can influence ecosystem dynamics and stability. Thus, the capacity to monitor reliably and consistently biodiversity in space and time is essential. In the last few decades, surface reflectance data were used with different degrees of success to monitor changes in functional diversity from remote sensing data.

In this contribution, for the first time the potential of sun-induced chlorophyll fluorescence in providing information on functional diversity of terrestrial ecosystems is investigated.

This was achieved exploiting high resolution airborne images acquired with the FLEX airborne demonstrator HyPlant. The HyPlant sensor consists of two modules: one hyperspectral imaging spectrometer covering the spectral region from the visible to the shortwave infrared and a second imager specifically designed for fluorescence estimation in the red and near-infrared regions.

The sensor was flown over forested areas characterized by different species composition and stand age. Different approaches to evaluate the functional diversity based on reflectance and fluorescence data were then assessed.

The heterogeneity across the study area was measured using two different metrics related to the diversity: the Shannon Entropy index, which takes into account the relative proportion of each pixels' value, and the Rao's Q diversity which explicitly accounts for distances among pixels' numerical values.

First of all, HyPlant raw data were georectified and atmospherically corrected to obtain top-of-canopy radiance and reflectance. Maps of sun-induced chlorophyll fluorescence at the far-red peak were then successfully obtained ($r2=0.73$, $p<0.001$, compared to top-of-canopy ground-based measurements acquired synchronously with the overflight) using the Spectral Fitting Method retrieval approach.

The entropy metrics were then calculated on maps of functional plant traits, far-red fluorescence and NDVI, which is the vegetation most commonly used in ecology. Rao's Q diversity performed better than the Shannon's index in characterizing the spatial heterogeneity of the investigated forests. Notably, the functional diversity patterns obtained calculating Rao's Q diversity on the fluorescence map better related to the functional diversity map used as a reference compared to those obtained applying the entropy metric on the NDVI maps. In particular, NDVI strongly underestimates the functional diversity across the study area and particularly in the juvenile stands, where the low entropy based on NDVI calculation shows that

NDVI cannot grasp the variability of the functional diversity.
Thus, the results obtained in this study show that the use of sun-induced fluorescence can improve our ability in functional diversity mapping compared to state of the art measures based on vegetation indices or reflectance.

Field-scale monitoring of drought stress using chlorophyll fluorescence with the coupled SCOPE-AgroC model

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Field-scale monitoring of drought stress using chlorophyll fluorescence with the coupled SCOPE-AgroC model
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Keywords: sun-induced chlorophyll fluorescence, drought monitoring, field spectroscopy, radiative transfer modelling, plant growth modelling
Droughts, which have become more frequent due to climate change, cause social, economic and ecological harm. Sun-induced chlorophyll fluorescence (SIF) is a promising indicator for droughts, given its close link to photosynthesis. This project is aims at developing a methodology to assess the effect of drought stress on SIF emission, particularly in the period before damage to the chlorophyll or plant structure has occurred. Therefore, we propose a coupled model consisting of SCOPE (van der Tol et al., 2009) and the plant growth model AgroC (Klosterhalfen et al., 2017). The SCOPE (Soil Canopy Observation, Photochemistry and Energy fluxes) model is a radiative transfer model which can be used to simulate SIF based on optical and thermal remote sensing observations above the canopy. AgroC allows to model plant development at the field scale, i.e. the net ecosystem exchange (NEE) of carbon dioxide and its two components, gross primary production (GPP) and ecosystem respiration (ER), consisting of an aboveground and belowground part. The model makes use of meteorological data, plant-specific parameters and soil characteristics. As photosynthesis is the main driver behind both SIF and GPP, GPP can be retrieved based on SIF. AgroC subsequently uses SIF based GPP retrievals in order to improve its parametrisation. Both SCOPE and AgroC are capable of predicting of transpiration. However, AgroC transpiration estimates consider possible drought stress, while SCOPE transpiration estimates do not. The ratio of both transpiration estimations therefore yields information about the stress conditions. To test the validity of the coupled model, we will perform a controlled field-scale experiment. Here, the objective is to measure the SIF using the FLoX instrument (JB Hyperspectral Devices, Düsseldorf, Germany) as well as meteorological variables (incident PAR, air temperature, wind speed, atmospheric vapour pressure and air pressure), vegetation properties (biomass, LAI, stomatal conductance, vegetation water content) and soil moisture at different depths. Running the coupled model using the in-situ data will result in a 'stress map', in which the stress factor is calculated at field scale. Comparing the measured data to UAV-based multispectral data and pulse amplitude modulation (PAM) measurements will provide information about the quality of the stress estimates.
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The effect of heat waves on the physiology and sun induced fluorescence of citrus trees

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Heat waves ('Hamsin') are a common phenomenon in the Mediterranean basin during springtime. It is important to understand plant response to such extreme events as their frequency and severity is increasing with global climate change. Sun induced fluorescence (SIF) offers a new means to detect canopy scale chlorophyll fluorescence, as an intrinsic indicator of changes in functioning of the photosynthetic apparatus. It is measured in two specific wavelengths, 687 nm (SIF_B) and 760 nm (SIF_A). Previous reports indicated correlation between ecosystem SIF_A and gross primary production (GPP). This suggests that chlorophyll fluorescence is linked to electron transport in the photochemistry pathway, but the effects of

different environmental factors on this signal and its relation to GPP is still unclear.

We studied the effect of 10 days seasonal heat wave in a citrus orchard in Israel from May to mid-June, when the maximum temperature ranged between 37-42ºC (compared with 23-28ºC in normal days), and vapor pressure deficit (VPD) values were 3-8 KPa (compared to 1-2 KPa in normal days). We used our mobile lab to carry out eddy covariance measurements of water, heat, CO2 and Carbonyl sulfide (COS) fluxes using a quantum cascade laser (QCL; QC-TILDAS-CS, Aerodyne Research, Billerica, MA, USA) and Infra-red gas analyzer (IRGA; LI-7200, LI-COR, Lincoln, NE, USA). Continuous SIF measurements were using a FloX system (JB hyperspectral devices, Düsseldorf, Germany). Additional pulse amplitude modulated (PAM) fluorescence measurements were conducted periodically using Mini-PAM (Heinz Walz Gmbh, Effeltrich, Germany).

During the study period, midday net ecosystem exchange (NEE) and GPP decreased by ~50%. Midday SIF_A signal decreased by similar values, compared to normal days, but SIF_B signal, remained unaffected. Comparing the daily patterns in SIF between normal and heat wave days, demonstrated similar patterns during the early morning and late afternoon hours, while VPD values were low. However, during mid-day, SIF_A signal decreased linearly with time during the heatwave, but remained steady during normal days. Electron transport rate (ETR) measured with the mini-PAM demonstrated similar patterns. In general, the daily trend of SIF_A and the ETR was found to be highly correlative (R2>0.8). The non-photochemical quenching (NPQ) values increased during the day with the increasing VPD, during the heat wave. Uptake of COS, sensitive to stomatal conductance, decreased during the day, while VPD values increased during the heat wave.

The results demonstrated a correlation between SIF_A signal and the electron transport rate. When stress conditions developed, plant stomatal conductance decreased (decrease in the COS flux), reducing the CO2 uptake and, in turn, fixation. This was associated with increase in NPQ probably to reduce over-excitation stress, while SIF_A decrease.

The results provide new insights to the effect of extreme events on the SIF signal, and its physiological significance, which can help its applications in Eco-physiological studies of plant response to climate change.

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Posters

Is remotely sensed SIF providing information on SIF yield?

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In order to evaluate the response of SIF yield to stress periods due to heat waves or droughts, we here use a machine learning algorithm to retrieve SIF (normalized by PAR) based on MODIS reflectance channels. The retrieval should no direct physiological relationship to biochemistry but we will demonstrate that it can still largely capture most stress periods. We will conclude regarding stress impact on chlorophyll and canopy structure.

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Global retrieval and assessment of terrestrial solar-induced chlorophyll fluorescence from TanSat satellite measurements

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The advent of the first Chinese carbon satellite, Chinese Carbon Dioxide Observation Satellite Mission (TanSat, also termed CarbonSat) launched on December 21, 2016, is the first Chinese satellite as an Earth Observation project intended to the monitoring and detection of atmospheric carbon dioxide (CO2). TanSat flies in a sun-synchronous, 700 km altitude orbit with a 13:30 ascending local time and a revisit period of 16 days. The Atmospheric Carbon dioxide Grating Spectraradiometer (ACGS), which uses the grating technique, is able to detect atmospheric O2 and CO2 absorption spectra in three narrow bands: near the O2-A band, weak CO2 band and strong CO2 band. Although the primary purpose of the TanSat mission is to retrieve the atmosphere column-averaged CO2 dry air mole fraction (XCO2), recent studies have also demonstrated that SIF can offer a new way for directly estimating the terrestrial gross primary production (GPP). The retrieval of solar-induced chlorophyll fluorescence on a global scale will been made possible due to the high spectral resolution measurements centered at 0.76 µm by the TanSat–ACGS spectrometer with a spectral resolution of 0.044 nm. Here, a micro spectral window (~ 2 nm) covered Fe Fraunhofer line is used to explore the potential of TanSat for solar-induced chlorophyll fluorescence retrievals. The basic idea for this retrieval in this work is distinguishing the in-filling effect of Fraunhofer line by fluorescence. The retrieval approach is based on the singular vector decomposition (SVD) statistical method to derive the fluorescence-free component in the solar radiance reflected by surface-atmosphere. SVD is a method used to factor real or complex matrices. Similar to Principal Component Analysis (PCA), it invelves the eigendecomposition of a large set of observations of correlated variables into a smaller set of uncorrelated signals called singular vectors. Normally, the singular value decomposition of an m×n real or complex matrix. One year available measurements are tested to produce the monthly gridded averages on the global scale. Some other remote sensing datasets are also used to validate the reliable of the fluorescence product derived in this work. An overall consistency of fluorescence intensity and spatial patterns of TanSat with OCO-2 fluorescence product on the global scale has been found in this work. And the high agreement between TanSat fluorescence retrievals and OCO-2 and other vegetation indices has consolidated the confidence of the potential and feasibility of TanSat fluorescence retrievals and opens the applications of TanSat measurements in the future scientific studies.

Keyword: TanSat; SIF; SVD; OCO-2; GPP

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Comparing satellite observations and measurements from the AtmoFLEX campaign using radiative transfer calculations

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Within the framework of the European Space Agency's (ESA) AtmoFLEX campaign, fluorescence and collocated atmospheric measurements have been collected to support the development of the fluorescence retrieval algorithm for the FLuorescence EXplorer (FLEX) mission. For this purpose, three instrumented sites in Europe have been selected, which are located in Germany, Italy and France. The sites locations cover different ecosystems focusing on agricultural areas and forests. Measurements at these sites address the scientific challenges of the retrieval of fluorescence based on satellite and airborne measurements. These sites measurements include land surface properties like reflectance or vegetation type and cover as well as atmospheric characterizations, namely aerosol load, type and height, humidity and temperature profiles. The instruments provide continuous measurements over months to generate statistically exploitable time series.

Point measurements of surface and atmospheric properties are not necessarily representative for larger spatial areas, for example a satellite sensor footprint. The spatial resolution of FLEX is approximately 300m x 300m, thus using a point measurement to develop the fluorescence retrieval algorithm is only a starting point. Within the framework of the ESA FLEXSense campaign, the HyPlant airborne sensor flew over the campaign sites in order to map fluorescence during June/July 2018. In addition, the Ocean and Land Color Instrument (OLCI) on board of Copernicus Sentinel-3B was reprogrammed for several acquisitions including the campaign sites during its commissioning phase. The reprogramming enabled OLCI to mimic the spectral characteristics of FLEX in specific parts of the electromagnetic spectrum. This three step scaling approach, point measurements – airborne measurements – satellite measurements, will foster the development of the fluorescence retrieval algorithm taking the influence of ecosystems, the weather and climate zones into account. The combined measurements are essential to validate and further develop the atmospheric correction scheme for FLEX, whilst the data may also be valuable for operational missions like Sentinel-3.

The radiative transfer model MOMO solves the radiative transfer equation of the atmosphere-ocean system using the Matrix Operator Method. MOMO allows simulating the spectral radiance at the bottom and the top of the atmosphere. MOMO has been fed with measurements gathered within the framework of AtmoFLEX, AErosol RObotic NETwork (AERONET) data and numerical weather prediction data by the HIRLAM model. For the radiative transfer computations, a bottom boundary condition is required. As spectrally high resolved reflectances are available for the sites from the Fluorescence boX (FloX) measurements, this is a suitable input to MOMO.

In order to validate the simulation approach, down welling radiances as observed by FloX are simulated. The simulation results of down welling radiances and the measured down welling radiances have been analyzed partially for the AtmoFLEX campaign. Additionally, a comparison of FloX and multi-filter rotating shadowband spectrometer (located at the research center Jülich, Germany) down welling irradiance will be presented.

The same atmospheric characterization can be used to simulate space-borne measurements. Possible satellite missions for comparing simulations and measurements include Sentinel-3 and Sentinel-2. First simulation results for satellite measurements are compared to the respective measurement. This approach can be extended to a longer time-series in order to get statistically founded results.

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Method For Acquiring and Comparing Spatially Explicit Measurements of Sun Induced Fluorescence on the Ground

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Sun-induced fluorescence (SIF) from plants is viewed among the broader scientific community as a valuable new source of information about plant functional status. As a result of the increasing interest, new SIF products derived from UAV, airborne, and spaceborne sensors are becoming increasingly available. Validation of such remotely sensed SIF maps requires spatially distributed ground measurements of SIF taken at the exact time of sensor overpass. However, because collecting spatially distributed SIF in larger areas is time-consuming, the majority of observations will be away from the exact time of overpass. Here, an outline for an empirical approach is proposed which corrects for the diurnal cycle and recalculate SIF for any given moment in time. The approach requires one single observation of SIF for the location of interest at any time, a diurnal SIF curve for the crop type (modeled or measured), and an estimate of the amount of biomass at the location of interest and the location of diurnal SIF measurement. To prove the feasibility of the method, we conducted a spatially distributed measurement of SIF in two crop fields modifying an existing hyperspectral point spectrometer (D-FLOX) for mobile use. Leaf area index (LAI), leaf chlorophyll content, plant height, and other relevant biophysical parameters were also recorded at each location. Alongside the mobile SIF sampling effort, an identical and intercalibrated device was installed on a permanent position to record the diurnal SIF cycle. Spatially distributed SIF from 46 locations (15 in sugar beet and 31 in winter wheat) collected on three separate dates between the hours of 10:00 and 14:00 were recalculated to solar noon using the proposed correction scheme and both raw and corrected SIF values were compared to LAI. We observed a better correlation and linear model performance against LAI for diurnal cycle corrected SIF. The locations in sugar beet were measured at the time of a low altitude overpass of the airborne hyperspectral sensor designed for SIF retrieval (HyPlant). Therefore, in a second step, SIF estimates in sugar beet were recalculated to the exact time of overpass and compared against the HyPlant derived SIF maps. In summary, a spatially explicit SIF sampling measurement protocol and simple empirical approach to correct for the distinct diurnal cycle of SIF are proposed. Such measurement approach can be used to study the spatial heterogeneity of SIF in small areas, to measure a large number of plots in field phenotyping set-ups, or to recalculate SIF in physical units for any given time of the day, e.g. for validation of airborne data.

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The evaluation of ecosystem service by satellite-based SIF in South-East Asia

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Primary production of terrestrial ecosystems supports all ecosystem services. Since climate conditions affect photosynthetic activity directly, recent global warming may damage or enhance the primary production of the ecosystem. Even if some extreme climate event damages the ecosystem, it would be recover and the resilience is important for the ecosystem service. The ecosystem resilience shows remarkable spatial variation because it depends on various environmental factors, including meteorological aspects and species composition of plants. Thus, to monitor the temporal trends in primary production enable us to identify the valuable ecosystem under climate changes in near future. To monitor the temporal changes in ecosystem function, Earth-observation satellite is a powerful tool. In recent years, satellite observed Solar Induced Fluorescence (SIF) is used to obtain the photosynthetic production or environmental stress for plants. The temporal changes in the satellite-based SIF would be good index to evaluate the ecosystem services.

By using temporal and spatial changes in SIF observed GOSAT, GOME-2, and OCO-2, we are trying to map the value of the ecosystem service in South-East Asia. Since these satellites have different spatial and time resolution, using multiple satellite data enable us to find extreme climate events easily. On the other hand, we have to consider the difference in observation time; GOME-2 observes in the morning whereas GOSAT and OCO-2 observe at midday. In this presentation, first, we will show the temporal variations of SIF in South-East Asia. In addition, we will show the map of ecosystems with strong resilience.

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LASVEG: a combined airborne instrumental platform for simultaneous measurements of laser-induced fluorescence, SIF, visible reflectance and vertical structure of the canopy

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The forthcoming FLEX mission of ESA will provide new fluorescence products, including the two chlorophyll fluorescence peaks in the red and far red, at unprecedented spatial and time resolution. New insights on the ecophysiological processes of vegetation at large scales are expected, linked to climate and environmental conditions changes. Chlorophyll fluorescence (ChlF) is tightly linked to photosynthetic processes as it competes with the other deactivation pathways of the absorbed energy, namely photochemical conversion and heat dissipation. Indeed, ChlF is routinely used at leaf level to quantify photosynthesis using active techniques. However, when using passive techniques, the link between sun-induced fluorescence (SIF) and photosynthesis still need to be clarified across spatial (leaf, canopy, ecosystem, regional, global) and temporal (hours, season, years) scales. We propose here a new airborne instrumental platform (LASVEG) that combines active and passive measurements of ChlF. Additionally, LASVEG will monitor the vertical structure of the canopy by laser waveform analysis. Laser-induced fluorescence (LIF) will provide a direct assessment of fluorescence quenchings at the canopy scale, offering a validation tool for fluorescence models and space data processing at the landscape and regional scale. LASVEG will be integrated on the research aircraft ATR42 from the French institution Safire. We present here the main technical features of LASVEG, as well as recent developments and first tests results.

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Characterization of sun-induced fluorescence and PRI anisotropy based on field spectroscopy data

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Recent studies have shown that sun-induced fluorescence (F) and Photochemical Reflectance Index (PRI) are characterized by noticeable directional variations, controlled by leaf and canopy structure (LAI, gap fraction and leaf inclination distribution - LIDF), pigments presence and sun-observation geometry that influence the light distribution, scattering and absorption inside the leaf and the canopy. Although in previous studies F and PRI were used for monitoring the photosynthetic activity, their anisotropic behavior was not yet fully characterized. An improved understanding of these directional variations can potentially help to disentangle directional from physiological responses in the continuous long-term optical measurements as well as to improve anisotropy correction models for airborne and spaceborne data. Therefore, the aim of this research is to contribute to the understanding of F and PRI directionality based on the field spectroscopy data.

The canopy bi-directional spectra were acquired with the FloX system (JB Hyperspectral Devices UG), specifically designed to measure F760 and F687 and visible-near infrared radiance. The FloX was coupled with a goniometer device, allowing to vary view zenith angles (VZA) and view azimuth angles (VAA). We collected multi-angular datasets of F and hemispherical–conical reflectance factor (HCRF) in Mediterranean tree-grass ecosystem over the herbaceous stratum in Las Majadas de Tiétar, Spain and over alfalfa, chickpea, corn and rice crops in Braccagni, Italy. Spectral measurements were acquired with a field of view of 25°. The view zenith angle varied from 0° to 45° in steps of 15° while the view azimuth angle varied from 0° to 315° in steps of 45°. These repeatable cycles were sampled continuously during a day from 9 am to 6 pm to characterize F and PRI anisotropy at different times of the day. In addition, canopy height, LAI and chlorophyll content were collected in the field, along with images for 3D canopy reconstruction.

The results showed, that multi-angular F760 and F687 of homogenous fully developed canopies have a distinct dome-like shape in the solar principal plane, with the maximum values occurring in the hotspot direction and minimum values in the forward scatter direction. In contrast, multi-angular F760 and F687 of row crops show a more complex hemispherical distribution. Overall, we observed strong positive correlation between F and HCRF at the corresponding wavelength (F760/R750 and F687/R680) in the solar principal plane, which was stable during the whole day.

Opposite to F variations, PRI exhibited strong directional responses for all homogeneous canopies with the highest values retrieved at VZAs corresponding to the forward scatter direction, and the lowest at the hotspot in solar principal plane, which can be explained by PRI sensitivity to sunlit and shaded canopy fraction.

The effects of sun-view geometry and LAI and LIDF parameters on spectro-directional F and PRI outputs were tested with the SCOPE model and compared with field observations. The obtained dataset of multi-angular F and PRI of five canopy types considerably contributes to our understanding of the anisotropic behavior of the signals.

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Quantitative assessment of Sun-Induced-Fluorescence maps from HyPlant airborne images using different quality criteria - Part II

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The ability to investigate the Earth's environment will be largely improved by hyperspectral satellite data. The FLuorescence EXplorer (FLEX) will be the first hyperspectral mission designed to monitor the photosynthetic activity of the terrestrial vegetation layer by using a completely novel technique measuring the sun-induced chlorophyll fluorescence (SIF) signal that originates from the core of the photosynthetic machinery. In preparation of the upcoming FLEX satellite mission that will be launched in 2022, a large field campaign, namely FLEXSense, was conducted in summer 2018 including representative study sites at several locations in middle and south Europe as well as North America.

During the various field activities, airborne data was acquired with the hyperspectral airborne imager HyPlant that consists of two sensor heads. The DUAL module is a line-imaging push-broom sensor providing contiguous spectral information from 380 to 2500 nm. The FLUO module measures radiance in high spectral resolution (0.25 nm) in the spectral region of the two oxygen absorption bands covering a range from 670 to 780 nm and facilitates a reliable retrieval of the chlorophyll fluorescence signal. Currently, two different algorithms are routinely used to retrieve red (SIF680) and far-red SIF (SIF760) from HyPlant data. Both methods exploit oxygen absorption bands for the retrieval. While the improved Fraunhofer Line Depth (iFLD) approach employs a semi-empirical atmospheric correction (i.e. using bare soils), the Spectral Fitting method (SFM) is coupled with a physically-based atmospheric correction (MODTRAN5 code).

A common method of testing the reliability of remotely-sensed SIF (in this study airborne maps) is the comparison with "ground truth" data. In many cases, however, ground measurements of SIF are not available or are too labor-intensive to be measured at regional level. For this reason, we developed an alternative approach based on image based quality criteria to assess the quality of airborne SIF maps. The set of quality criteria (e.g. signal-to-noise ratio, correlation with vegetation indices, plausibility checks, etc.) helps identifying and quantifying errors and artifacts in retrieved SIF maps.

In this contribution, we outline the defined set of quality criteria and demonstrate their capability to determine the quality of individual SIF maps derived from HyPlant images acquired during the 2018 FLEXSense campaign. The application of the proposed quality features proved to be a valuable tool for assessing the quality of SIF maps derived from HyPlant airborne data. We suggest to apply this set of criteria in addition to validation attempts that employ ground reference measurements. This allows providing complementary information about the SIF retrieval accuracy and the quality of entire SIF maps.

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Linking spatial Fluorescence patterns to soil and atmospheric properties in a heterogeneous agriculture landscape

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There are strong interactions between soil properties, plant growth and atmosphere. We use sun-induced Fluorescence (F) of vegetation to obtain remotely information about the plant physiological status that can be linked to soil and atmospheric properties, improving our understanding of energy and matter flows. F is a signal closely related to the actual rate of photosynthesis and vegetation stress. It reflects functional limitations of the photosynthetic carbon gain and can be measured remotely in solar and atmospheric absorption lines using high performance spectrometers. The future satellite mission of The FLuorescence EXplorer (FLEX) will allow for the first time monitoring of F over the globe providing the hyperspectral data with required resolution.

During several years we have collected data for spatial analyses using the high performance imaging spectrometer HyPlant, measuring in wavelength ranges 380 – 970 nm with resolution 4.2 nm, 970 – 2500 nm with resolution 13.5 nm and 670 – 780 nm with high spectral resolution of 0.26 nm. The HyPlant data were processed using iFLD (Improved Fraunhofer Line Discrimination) and SFM (Spectral Fitting Method).

Data were recorded on a ca. 14x14 km2 area around Forschungszentrum Juelich (Germany) with a spatial resolution of 3 m per pixel. Land cover of this region is classified mostly as crop fields, some mixed forest patches and some residential/industrial areas. Also two pit mining zones are presented in the scene. Within this large area, another specific area used mostly for crop production and with a size of ca. 1.5×5 km2 near a town of Selhausen was chosen to acquire data with 1 m resolution. Selhausen area was better characterized in terms of land use classification, soil properties and ground measurements of F and reflectance by FloxBoxes. Furthermore, an Eddy Covariance (EC) tower was present in this area.

We have analyzed data collected by HyPlant in the footprint of a scanning passive microwave radiometer (MWR) measuring integrated water vapor (IWV). This

allows us to link the plant functioning to the regional atmospheric water vapor patterns. For this purpose we have used F and common vegetation indices by comparing them to values of IWV for all azimuth directions measured during the time of the HyPlant overflight above the region of interest.
Recently, different crops were investigated and it was shown that the within-field heterogeneity of F caused by differences in plant performance is related to specific subsurface structures identified by quantitative multi-coil electromagnetic induction (EMI) data inversions. The inverted electrical conductivity of the ploughing layer showed minor correlation to fluorescence data, while the correlation between the subsoil conductivity and far-red fluorescence indicate a significant influence of the subsoil on plant performance, especially during dry periods. Moreover, distinct F patterns were created by differences in water-holding capacity of soil at depths of 1 m and deeper, which means that F data can contain soil moisture information at depth. Together with quantitative EMI data inversions, this information can be used to reduce existing uncertainties in assessing the efficiency with which plants access and use the soil water/nutrient resources.

The extensive dataset collected and processed during the last years allows us to perform detailed analyses of interactions within the soil-plant-atmosphere system. The aim of this work is inclusion of such interactions into soil-plant-atmosphere models for root water uptake and evapotranspiration processes as well as into harvest predictability tools.

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Mechanistic modeling of leaf gas exchanges expands the utility of SIF into estimation of ecosystem transpiration

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Plant gas exchange through leaf stomata plays a critical role in terrestrial water and carbon cycles, regulating the trade-off between photosynthetic carbon gain (A) and transpirative water loss (T). This is often characterized by plant water use efficiency (WUE – the ratio of A to T), a critical ecosystem indicator for how plants have adapted (or will adapt) to the physical limitations of their changing environment. Given that the diffusive fluxes of A and T across stomatal pores are linearly proportional to stomatal conductance, the conventional WUE parametrization, a nearly-linear function of atmospheric CO2 partial pressure, fails to account for the information content of plant stomatal configuration in response to other emerging environmental controls (such as soil moisture, plant hydraulics and/or vapor pressure deficit). This is of particular importance for the understanding and predictability of water and carbon cycles under current and future climate change scenarios, where the conventional assumption of a linear (one-to-one) correlation between A and T would tend to propagate relatively large errors and uncertainties into model estimates of T informed by A and WUE. Capitalizing on recent progress made in mechanistic modeling of leaf-level gas exchange processes, this study aims to provide an improved representation of physical mechanisms constraining WUE. The new parametrization explicitly accounts for the stomatal response to environmental changes reflected in a varying intercellular CO2 concentration (as opposed to the traditional assumption of a constant value). Given the difficulties in quantifying intercellular CO2 concentration dynamics at operational scales, we propose a theoretical solution in which the supply of CO2 via the stomata (A) and biochemical demand for CO2 are constrained by the balance between loss of water vapor from the leaf to the atmosphere (T) and supply of water from soil to the leaf through the soil-root-xylem system. We test the model estimates of A and T using field observations in a mixed forest and cropland, and discuss its potential benefits to expand the utility of remotely sensed photosynthetic (A) proxies, such as SIF, into estimation of ecosystem T and prediction of carbon-water relations in a changing environment.

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Canopy architectural influence on the interpretation of the biophysical parameters and sun-induced chlorophyll fluorescence variability: A small-scale laboratory experiment.

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Within preparation of the upcoming FLuorescence EXplorer (FLEX) satellite mission, several chlorophyll Sun Induced Fluorescence (SIF) studies induced a significant knowledge on vegetation physiological and photosynthetic dynamics. To understand these complex dynamics, biophysical parameters related to light use efficiency, concentration of foliage pigments

or leaf photochemical status are required to complement the information provided by SIF. Although all these parameters need an accurate estimation of the at-target incoming radiance, the most extended approach is to use the top of the canopy incoming radiance, while neglecting the vegetation structural heterogeneity. Therefore, it is necessary to investigate the impact of the canopy structure on radiance-derived measurements.
The main objective of this work is to study the effect of the vegetation architecture, i.e. foliage geometry and clumping, on spectroscopic estimation of vegetation biophysical parameters crucial in SIF studies. This study shows the variability and differences between measurements of the top of canopy radiance obtained from a horizontal white reference panel and as measured at the surface of photosynthetically active leaves. Additionally, it demonstrates, on few examples, the canopy structural influence on quantitative estimations of vegetation indices related to photosynthetic processes, such as an incoming leaf photosynthetic active radiation (PAR), chlorophyll content (approximated by MTCI), and photoprotection status (approximated by PRI).
In this study, crowns of healthy beech saplings (Fagus sylvatica L.) were measured in laboratory under stable environmental and illumination conditions. Top-of-canopy spectral measurements were performed with a push broom system, which consists of a HySpec VNIR scanner (Photon Systems Instruments, around 1 nm spectral resolution and 350-900 nm spectral range) and a halogen lamp. Small white Spectralon reference panels (1 cm2) were attached to several leaves with varying orientation angles at different depths of the canopy vertical profile. Additionally, a larger white reference panel was allocated horizontally next to the plant, perpendicular to the sensor optical plane, covering the entire field of view of the instrument and providing the top-of-canopy radiance.
This work is aiming at development of new methods for correcting the canopy structural influence in the remote sensing measurements of vegetation physiological state traits, in support of the development of high-level FLEX products.

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Measuring sun-induced fluorescence at different scales: Overview over instruments, measurement setups, protocols and their application at leaf and canopy scale

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Field spectroradiometric measurements as well as imaging spectroscopy study the interrelationships between the spectral characteristics of objects and their biophysical attributes in the field environment. With the advancements in sensor technology also finer spectral features can be measured by these instruments.
One example is sun-induced fluorescence (F).
Still, measuring and interpreting the F signal remains challenging, both regarding the post-processing and F retrieval step with factors driving the offset between the emitted versus the retrieved F signal, and the F interpretation step, with factors related to the dynamical physiological behaviour of vegetation and its structural effects. The first step includes factors related to the instrumental responses, specifications and the platform/measurement set-up.
To meet these challenges, many researchers have worked within the framework of an european cooperation in science and technology (COST) action ES1309 to develope innovative optical tools for proximal sensing of ecophysiological processes (OPTIMISE). To make this information available, the OPTIMISE community has compiled three papers on instrument characterisation, measurement setups and protocols and retrieval techniques. These reviews aim summarize the state-of-the-art for highly precise radiance measurements with focus on F to pursue the almost 10 years old review paper of (Meroni et al., 2009).
With this poster we would like to present the main outcomes on the measurement setups and protocols used to measure F at the leaf to canopy scale, including the discussion on important metadata to capture along with the measurements.

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Temporal upscaling solar-induced chlorophyll fluorescence from the instantaneous to continuous scale causes an improved correlation with gross primary productivity

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Solar-induced chlorophyll fluorescence (SIF) is closely linked to the photosynthesis of plants and has the potential to estimate gross primary production (GPP) at different temporal and spatial scales. However, remotely sensed SIF at ground or space level is usually instantaneous, which cannot represent the daily total SIF. The temporal mismatch between instantaneous SIF

(SIFinst) and daily GPP (GPPdaily) impacts their correlation across space and time. Previous studies have upscaled SIFinst to the daily scale based on the diurnal cycle in the cosine of the solar zenith angle (cos(SZA)) to correct the effects of latitude and length of day on the variations in the SIF-GPP correlation. However, the important effects of diurnal weather changes due to cloud and atmospheric scattering were not considered. In this study, we presented an SIF upscaling method using photosynthetically active radiation (PAR) as a driving variable. First, a conversion factor (i.e., the ratio of the instantaneous PAR (PARinst) to daily PAR (PARdaily)) was used to upscale in-situ SIF measurements from the instantaneous to daily scale. Then, the performance of the SIF upscaling method was evaluated under changing weather conditions and different latitudes using continuous tower-based measurements at two sites. The results prove that our PAR-based method can reduce not only the latitude-dependent but also the weather-dependent variations in the SIF-GPP model. Specifically, the PAR-based method gives a more accurate prediction of diurnal and daily SIF (SIFdaily) than the cos(SZA)-based method, with decreased relative root mean square error (RRMSE) values from 42.2% to 25.6% at half-hour intervals and from 25.4% to 13.3% at daily intervals. Moreover, the PAR-based upscaled SIFdaily had a stronger correlation with the daily absorbed PAR (APAR) than both the SIFinst and cos(SZA)-based upscaled SIFdaily, especially for cloudy days with a coefficient of determination (R2) that increased from approximately 0.5 to 0.8. Finally, the PAR-based SIFdaily was linked to GPPdaily and compared to the SIFinst or cos(SZA)-based SIFdaily. The results indicate that the SIF-GPP correlation can obviously be improved, with an increased R2 from approximately 0.65 to 0.75. Our study confirms the importance of upscaling SIF from the instantaneous to daily scale when linking SIF with GPP and emphasizes the need to take diurnal weather changes into account for SIF temporal upscaling.

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Separating physiological from sun-view geometry effects with a high resolution proximal hyperspectral imager on the Tumbarumba forest flux tower

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To better link dynamic canopy physiology to the spectral signal we developed a fully automated hyperspectral and thermal monitoring system installed on a flux tower at a mature Eucalypt forest site – Tumbarumba (Australia). The Tumbarumba site is a member of FLUXNET, SpecNet, and a CEOS Land Product Validation (LPV) SuperSite.

High-resolution multi-angular imagery of tree crowns is acquired by the Headwall VNIR N-series line scanner, enabling vegetation and non-vegetation classification, in addition to sunlit and shaded pixel separation. Radiance is measured in the 400-800 nm range (538 wavelength bins), coincident with hemispherical irradiance measurements for computation of a reflectance factor. Consequently, the monitoring system has been used to characterise the significant sun and sensor geometry effects at both diurnal and seasonal time scales.

Our recent work has characterized the seasonal effects on the PRI signal, likely caused by changing pigment concentrations. Similar to other vegetation types we found the seasonal constitutive changes in PRI far outweighed the dynamic facultative changes at the daily to weekly time-step. This finding was further corroborated by field sampling, controlling for lighting and structure, where the natural constitutive variation among trees and within crowns was greater than facultative PRI changes varying in response to direct and diffuse lighting conditions. Results characterizing canopy BRDF from the proximal sensing system will be presented alongside relationships between corrected spectral indices and flux tower GPP. The importance of linking leaf-level measurements with site-scale proximal measurements is emphasized.

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Return of experience from the Sentinel-3 Tandem and lessons learned for FLEX

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During its commissioning phase, Sentinel-3B was flying in close formation (30 seconds) with Sentinel-3A. This presentation will highlight some of the lessons learned from this tandem phase that can be applied to the future FLEX-Sentinel-3 tandem.

First, the tandem phase has proved extremely useful for supporting commissioning operations, including validation of performances and investigation of anomalies. The tandem configuration allows inter-sensor validation with an unprecedented level of accuracy, and provides a unique opportunity to quantify uncertainties on products. For FLEX and Sentinel-3, this means that a very fine inter-calibration of the sensors will be most probably reachable, which will benefit not only FLEX but also the Sentinel-3 optical mission and vegetation products. As an illustration, we will show how uncertainties on OGVI products can be assessed thanks to tandem data.

To fully benefit from the tandem phase, we have shown that all known instrument differences shall be carefully considered. In particular, fine spectral response function differences have to be accounted before comparing the measurements. This concerns differences not only between instruments but also within the field of view. To this respect, the fact that the swath of FLEX will remain within the swath of a single OLCI camera is critically important.

A third outcome of the tandem phase is the possibility to assess the impact of the formation time lag on the observation conditions, (in particular cloud motion and viewing geometry). At the end of the tandem phase, Sentinel-3B has been manoeuvred to drift slowly away from Sentinel-3A. It is therefore possible to analyse quantitatively the impact of the time difference on the measurements. Effects of cloud motion is apparent even at short time scales (30 s) but has been shown to be relatively easy to handle. In fact, the very fact that clouds are moving or evolving make them easy to detect and discriminate from other bright objects. The impact of viewing conditions on TOA observation starts becoming important only for larger time differences, except on very reflective surfaces (sun glint). These results indicate that a 30-second formation could be sufficient to meet FLEX observation requirements.

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Time series of Sun-Induced Fluorescence, Gross Primary productivity and Transpiration in a Mediterranean grassland

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Sun induced fluorescence (SIF), the radiation flux emitted by plant chlorophylls molecules in the 650-800 nm spectral window, is considered an indicator of photosynthetic performance. Recently it has been shown that SIF can track changes in light use efficiency (LUE), and therefore it is a good predictor of gross primary production (GPP) at various scales, from leaves and ecosystem to regional and global scale.

Although the GPP – SIF relationship has been investigated at multiple scales, little is known about SIF dynamics at ecosystem level and its links with GPP and transpiration (T). Consequently, the understanding of the mechanistic relationship between SIF GPP and T is limited. Recently, there is evidence that suggests that SIF could be a reliable tool to monitor not only GPP, but also T, as T is mediated by stomatal conductance and typically tightly coupled with photosynthesis.

As new instruments for proximal remote sensing of SIF are being developed, collecting time series of SIF with high temporal frequencies at flux tower locations is now operational. Additionally, modelling of SIF emission and transfer within the canopy has become increasingly accurate as models such as the radiative transfer and energy balance model SCOPE (soil canopy photosynthesis and energy) are being validated at different ecosystems.

Time series of SIF are characterized by high temporal frequency and when paired with time series of T derived from sap flow or from partitioning eddy covariance evapotranspiration, and GPP derived from eddy covariance, they can open new perspectives to understand the degree of temporal variability in GPP, T and SIF that occurs at the ecosystem level.

In this contribution we make use of data collected at the research site Majadas de Tietar, a tree grass ecosystem equipped with multiple ecosystem and sub-canopy eddy covariance towers and a Fluorescence BOX (FLOX, JB Hyperspectral Devices, Düsseldorf, Germany) that collects at high temporal resolution Hyperspectral measurements for SIF retrieval. Our objective is to evaluate the relationship between GPP, T and the ecosystem scale water use efficiency (WUE) with SIF.

Making use of both data-driven techniques and the SCOPE model, we aim to investigate the degree of coupling between GPP, T, WUE and SIF at different time-scales as well as the relationships between the fluxes and SIF. SCOPE model runs forward based on observations of model parameters to understand the factors controlling the relationship between transpiration-WUE-GPP-SIF from daily and seasonal time scale. Preliminary results will be shown in this contribution.

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Phenological changes in GOSAT SIF in temperate vegetations in Japan

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In temperate region, leaf phenology, including the timing of onset and offset of leaves and temporal changes in ecophysiological parameters of single leaf determine the annual carbon gain of the vegetation. Since the leaf growth and senescence are depend on temperature condition, climate change might strongly affect the phenological pattern. Thus, to find the effect of climate change on the vegetation, it is effective to monitor the leaf phenology. Satellite remote sensing is useful tool to monitor the temporal and spatial variations in the structure and physiological traits of canopy. Previous studies have shown that satellite-observed vegetation indices, such as NDVI and EVI are available to detect leaf onset and offset. However, it is difficult to monitor leaf growth and senescence by satellite observation because those indices indicate only amount of leaves in the canopy. In recent years, solar-induced chlorophyll fluorescence (SIF) has observed by satellite such as GOSAT, GOME-2 and OCO-2. GOSAT-2, launched on 29th October 2018 will also observe SIF. Since SIF linked with photosynthetic activity itself, it might be suitable index for leaf phenology. In present study, we focused on three areas with different vegetation types and temperature conditions in Japan and showed temporal changes in SIF observed by GOSAT in those area. Those three areas showed different seasonal pattern in SIF. We will discuss main cause of the phenology in SIF in temperate region and availability of GOSAT and GOSAT-2 SIF as an indicator of leaf phenology.

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Towards field-deployable fluorescing reference targets

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The retrieval of solar induced fluorescence (SIF) from plants and canopies makes use of specific schemes using either Fraunhofer or Oxygen-absorption bands. Proper calibration of the retrieval schemes is problematic as the fluorescence signal of Chlorophyll adds to a background having peculiar reflectance properties, such as that of the vegetation. The idea of artificially adding known amounts of light in the fluorescence bands to a naturally fluorescing background (vegetated surface) is certainly an interesting option for calibration, even if the fluorescing background is naturally subjected to rapid changes in response to light, temperature and/or stress. To overcome such limitation, the idea was explored to create an "artificial fluorescing target" by incorporating fluorescent dyes on an artificial coating mimicking the reflectance response of the vegetation. This type of coating is well known especially in military applications for the "camouflage" of sensible targets on the ground. This poster illustrates the preliminary results of the incorporation of fluoresceing dyes in a camouflage background and illustrates the reflection spectra which may be obtained as well as the SIF retrieval. Potential applications of this type of artificial targets for the calibration of ground and airborne SIF sensors as well as for the validation of atmospheric correction schemes is finally discussed.

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Validation of atmospheric correction: Collaboration and exchange between Copernicus Sentinel-2 and Sentintel-3 teams?

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The Copernicus programme is a European initiative for the implementation of information services dealing with environment and security, mainly based on observation data received from Earth Observation satellites. In the frame of this programme, ESA launched the Copernicus Sentinel-2 and Sentinel-3 optical imaging satellites and is preparing the FLEX-Explorer mission. These satellites deliver a new generation of optical data products designed to directly feed downstream services mainly related to land monitoring, emergency management and security. Synergistic data analysis involving FLEX, Sentinel-3 and Sentinel-2 missions is an upcoming topic which combines and exploits the spatial and spectral benefits of each of these missions. However, this can only be successful if the uncertainties in the data to be combined are known and reported in a similar way.

Atmospheric correction of satellite observations is a precondition for most higher-level applications. Development of atmospheric correction processors includes their validation, which provides performance of the algorithm and uncertainty of resulting products. Even if different atmospheric correction algorithms are developed and used for Sentinel-2 and Sentinel-3 data and are being developed for FLEX-mission, there is a high synergy potential regarding validation.

The presentation demonstrates the current validation methodology for atmospheric correction of Sentinel-2 data. Aerosol optical thickness and water vapour outputs of atmospheric correction algorithms Sen2Cor and PACO can be directly compared with reference data available from AERONET sunphotometers. Performance analysis of surface reflectance (SR) is done by comparison of processor outputs with so called AERONET-corrected SR. AERONET-corrected SR is computed from the Level-1C Top-of-Atmosphere data using a radiation transport model with input data provided by AERONET. This analysis including a radiation transport model has to be completed by SR measurements gathered during ad-hoc campaigns. One aspect of potential synergy between Sentinel-2 and Sentinel-3 validation of atmospheric correction can cover sharing of campaign data and organization of joint ad-hoc campaigns. Finally, discussion about the validation protocol and statistical metrics currently applied for reporting atmospheric correction performance is of high interest.

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Seasonality in solar induced chlorophyll fluorescence and light use efficiency in boreal Finland

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Solar induced chlorophyll fluorescence has been shown increasingly to be a useful proxy for the estimation of gross primary productivity (GPP), with an emergence of documented studies using ground based- airborne and satellite retrievals. In the work presented here we aimed to explore the seasonality in a continuous time series of high resolution optical data, solar induced fluorescence (hereafter SIF) retrievals and their relation to gross primary production (GPP), canopy light use efficiency (LUE) and pulse amplitude measures of efficiency. SIF was calculated using infilling in two bands from the incoming and reflected radiance using a pair of Ocean Optics USB2000+ spectrometers operated in dural field of view mode, sampling at a 30 minute time step using custom written automated software, from early spring through until autumn in 2011. The optical system (see Drolet et al, 2014 for details) was mounted adjacent to an eddy covariance system, over an 80m Scots pine canopy at the Hyytiälä Forestry Field Station in Finland. A Monitoring PAM was mounted within the canopy adjacent to the footprint sampled by the optical system. Following correction of the SIF data for O2 and structural effects, SIF, LUE, PRI and NDVI exhibited a distinct seasonal pattern that followed GPP sampled by the eddy covariance system. Due to the complexities of solar azimuth and zenith angle over the season on the SIF signal, correlations between SIF, SIF yield, GPP and LUE were restricted to SZA<50o, under strictly clear sky conditions which resulted in only modest correlations (~r2=0.3). The diurnal responses of SIF, SIF yield and PAM parameters (F/Fm’) and meteorological parameters demonstrated improved agreement over the diurnal cycle. This study found that optical sampling at this fine spectral, spatial and temporal resolution, the retrieved SIF signals did not perform well without a structural correction, and even then heavy filtering of the data was required to include only the highest SZA and SAA conditions which resulted in convincing relationships with GPP and LUE

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Sun-Induced Fluorescence and Spectral Vegetation Indices for Heterogeneous Ecosystems and Diverse Peatland Plant Communities

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Peatlands are one of the vital ecosystems of the earth due to accumulation of carbon in the peat, big biodiversity, and occurrence of distinctive vegetation species. However, due to huge heterogeneity of the surface, internal diversity, environmental gradients, it is always a challenge to understand peatland vegetation functionality through remotely sensed vegetation indices (VIs) and sun-induced fluorescence (SIF) signals. Previous studies of SIF were mostly restricting their observation on homogenous ecosystems like croplands, grasslands, and forest areas. Hence, considering this knowledge gap this study will demonstrate the relationships between VIs and SIF from heterogeneous ecosystems and peatland vegetation communities based on data collected during the SWAMP airborne campaign in 2015.

Imaging spectrometer 'HyPlant' (the airborne demonstrator for the ESA FLEX mission) was flown for the first time over the extremely heterogeneous peatland and surrounding ecosystems during the SWAMP campaign held on 11th July 2015, within the COST Action OPTIMISE, EUFAR, and ESA funded SWAMP Summer school and under the FLEX-EU (ESA). Rzecin (POLWET) peatland is located in central-western Poland (Wielkopolska region) within Noteć Forest (52°45' N latitude,16°18'E longitude, 54 m asl). The entire Rzecin peatland and its surroundings are enriched with diverse vegetation groups of vascular and non-vascular plant communities. The target of this study is to explore a comparative analysis of SIF signals and VIs and their relationships obtained from different vegetation groups at ecosystem level (forest, grassland, peatland) and from diverse peatland plants at plant communities level. The VIs and Spectral Fitting Method (SFM) retrieved SIF maps (O_2A and O_2B) were validated (VIs: R^2 = 0.79-0.91; SIF: R^2 = 0.87-0.92) in support of measured ground spectra before any analysis. A clear positive trend with a good agreement (R^2 = 0.55-0.91) and statistically significant ($p<0.01$) relations have been observed between SIF bands (O_2A and O_2B) and greenness indices (SR, NDVI) whereas, a negative trend with a good agreement (R^2 = 0.40-0.71) and statistically significant ($p<0.01$) relation have been found between PRI and SIF at large scale vegetation group. Due to huge diversity and low SNR (Signal to Noise Ratio), no such agreements were established between SIF bands and VIs at smaller scale peatland plant communities, except for some isolated homogenous patches of meadows. Filling the knowledge gap, this work provides a proof that the relationships between SIF bands and several VIs are very complex for heterogeneous ecosystems.

Acknowledgment

The Research was co-funded by the COST Action ES1309 OPTIMISE, FP7 European Facility for Airborne Research (EUFAR), FLEX-EU ESA (Contract No. 4000107143/12/NL/FF/lf CCN3) and European Space Agency which supported the SWAMP training course (6-16th of July 2015) and airborne campaign on 11th of July 2015. Analyses of the data were supported by the Polish National Research Centre within the project No 2016/21/B/ST10/02271 (Sun Induced florescence and photosynthesis of peatland vegetation response to stress caused by water deficits and increased temperature under conditions of climate manipulation experiment).

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Can We Measure Sun-Induced Chlorophyll Fluorescence Emitted by Biocrusts?

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Biocrusts, a combination of autotrophic and heterotrophic organisms including mosses, lichens, liverworts, cyanobacteria and algae are a key component of the semi-arid and arid regions of the Earth. Besides playing a critical role in the stabilization and development of drylands, biocrusts contribute appreciably (~7%) to the global carbon fixation. Nowadays, drylands cover about 45% of the Earth's land surface, and are expected to expand by up to 23% by the end of this century. For these reasons, understanding biocrusts functioning and quantifying their imprint on the global carbon dynamics is key to establish ecosystem feedbacks to the climate system. In this framework, Remote Sensing (RS) of sun-induced chlorophyll fluorescence (F) might be a promising tool for obtaining new insights into biocrusts functional state.

In this contribution we aimed at understanding if the weak F signal emitted by biocrusts can be passively detected using high-resolution radiance measurements. In particular, this contribution aimed at: i) quantifying the F emission of biocrusts at the red and far-red emission peaks; ii) understanding the relative contribution of the different biocrust components by relating the F signal to the fractional cover of the endmembers.

At this purpose, we acquired high-spectral resolution radiance measurements on 37 biocrust samples collected in a dryland area located in central Spain (Aranjuez). The spectral measurements were collected under direct solar irradiance using the FLoX instrument (JB Hyperspectral Devices, Germany). The core of this system is a QEPro (Oceanoptics, USA) spectrometer covering the red and near-infrared regions (650-800 nm), allowing to detect F at both the red and far-red peak. The samples were measured before and after watering in order to determine the effect of biocrusts activation on the measured F signal. F was retrieved using spectral fitting methods at the red and far-red emission peaks.

Results showed that active biocrusts emit F with a typical two peaks spectrum. However, while vascular plants are typically characterized by a higher emission in the far-red, biocrusts showed a higher signal in the red. This distinctive behavior is explained by the different structure and chlorophyll content of biocrusts compared to vascular plants and might be exploited to detect and monitor active biocrusts from remote. Results also showed that moss-dominated biocrusts emit higher F compared to lichen-dominated ones.

Overall, this analysis demonstrated the feasibility of passively detecting the faint F signal emitted by active biocrusts, disclosing the possibility to obtain new insights into biocrusts functional state. This opens great opportunities to understand and monitor challenging environments such as drylands from the local to the global scale.

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FLUORT: a GUI FLUOresence Retrieval Toolbox for automating and optimizing sun-induced chlorophyll fluorescence retrieval from spectroscopy data

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Sun-induced chlorophyll fluorescence (SIF) is the light re-emitted by plants in the red and far-red region of the spectrum following the light absorption by photosynthetic pigments. The interest in SIF has recently led to the creation of multiple spectroscopy systems for the acquisition of this data at various scales, (ground-based, airborne or even spaceborne with the upcoming FLEX mission). However, a precise retrieval of SIF is mandatory to enable using this subtle signal for applications such as monitoring the plant's photosynthetic capacity. SIF retrievals methods are based on incident solar irradiance and target radiance measurements. Hece, the main challenge relies in disentangling the reflectance radiance (RFL) and emitted SIF from the measured target radiance (L).

To achieve this, most of the SIF retrieval methods exploit the Fraunhofer line depth (FLD) principle. By combining measurements of solar irradiance (E) and L (FLD and 3FLD) or E and apparent reflectance (aRFL = RFL + SIF) inside and outside the Fraunhofer line it is possible to decouple SIF from RFL. A crucial step when implementing the FLD approaches, however, is to model how E, L, and aRFL vary in the absence of the absorption line. To do so, a precise function to interpolate E, L, and aRFL inside the absorption line needs to be defined. Accordingly, an accurate interpolation strategy is needed, which takes into account the following factors: (1) a good definition of the starting point of each absorption band, (2) selection of points outside the absorption bands to perform the interpolation, and (3) an appropriate interpolation method.

Given the variety of SIF retrieval methods at our disposal, along with the methods´variables that can be modified, it implies that multiple optimization options have become available for obtaining precise SIF retrieval. In order to streamline and automate this process of fine tuning, it motivated us to develop a new fluorescence retrieval toolbox called FLUOrescence Retrieval Toolbox (FLUORT). FLUORT has been developed in a GUI framework within the context of Automated Radiative Transfer Models Operator (ARTMO) scientific software package.

In FLUORT, we have implemented the most common SIF retrieval methods available derived from the FLD, extended FLD (eFLD), improved FLD (iFLD), Peak Height Method (PHM) and Spectral Fitting Method (SFM). The GUI interface allows the user to enter measurements of radiance and irradiance data, and to choose between any combination of retrieval and interpolation methods. FLUORT first assesses the best bands for interpolation, and after a first interpolation the user can optimize: (1) the interval defined for limiting the absorption bands, (2) the points used to take part in the interpolation, (3) the interpolation method, and (4) the free variables of the interpolation methods. The toolbox directly shows the impact of the optimization on the interpolated E, L, aRFL outputs.

In general, FLUORT automates the estimation of SIF at the two oxygen absorption bands for each input radiance and irradiance dataset. Moreover, in case the user adds a reference SIF, a validation process can be employed that compares the reference data against the calculated one. After passing the beta phase, the toolbox will become freely available to the community.

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Sun-induced chlorophyll fluorescence: retrievals methods and practical cases for proximal sensing.

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The growing interest on the proximal sensing of sun-induced chlorophyll fluorescence (F) has been boosted in by space-based retrievals and up-coming missions such as Earth Explorer of the European Space Agency FLuorescence EXplorer (FLEX). In the last ten years, field spectroradiometers have improved in spectral resolution (Full Width Half Maximum, FWHM ≤ 0.3nm) and signal-to-noise ratio (SNR ~ 1000:1). This currently allows the exploitation of sophisticated retrieval algorithms (e.g., spectral fitting methods) exploiting resolved narrow absorption feature in the irradiance spectrum. However, F retrieval is very sensitive to uncertainties, and results strongly depend on the instrumentation, the measurement protocol and the retrieval method. In the last four years, the COST Action ES1309 OPTIMISE "Innovative optical tools for proximal sensing of ecophysiological processes" has gathered efforts to address these three challenges in the proximal sensing of F in three separated and connected works submitted to this conference.

A major source of error when retrieving F is the proper implementation of the different retrievals methods. Thus before using F to understand vegetation dynamics a precise retrieval of F is mandatory. This study is divided in two sections; first, we evaluated the uncertainties in F retrievals (i.e. FLD approaches and Spectral Fitting Method, SFM) for a combination of state-of-the-art spectrometers suited to measure F (i.e. ASD, MAYA, HR400, QEPRO). Secondly, we evaluated how an erroneous implementation of the different retrievals methods (i.e. absorption bands range selection, proper interpolation at the absorptions bands, proper selection of the point inside de absorption bands…) increase the uncertainty when retrieving F. The aim of this work is to provide the scientific community a reference study where they can evaluate the precision of their F measurements based on both their instrument configuration and the retrieval method used.

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Instrumental considerations in the proximal sensing of sun-induced chlorophyll fluorescence

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The growing interest on the proximal sensing of sun-induced chlorophyll fluorescence (F) has been boosted in by space-based retrievals and up-coming missions such as Earth Explorer of the European Space Agency FLuorescence EXplorer (FLEX). In the last ten years, field spectroradiometers have improved in spectral resolution (Full Width Half Maximum, FWHM ≤ 0.3nm) and signal-to-noise ratio (SNR ~ 1000:1). This currently allows the exploitation of sophisticated retrieval algorithms (e.g., spectral fitting methods) exploiting resolved narrow absorption feature sin the irradiance spectrum. However, F retrieval is very sensitive to uncertainties, and results strongly depend on the instrumentation, the measurement protocol and the retrieval method. In the last four years, the COST Action ES1309 OPTIMISE "Innovative optical tools for proximal sensing of ecophysiological processes" has gathered efforts to address these three challenges in the proximal sensing of F in three separated and connected works submitted to this conference.

In these addresses the instrumental challenges in the proximal sensing of F. Spectroradiometers are passive sensors sensitive to spectral radiation, as well as other environmental variables. In this work we simulate a state-of-art spectroradiometer to model the impact of different instrumental noises and biases on the retrieval of F. We first combine a sensor emulator, experimental and realistically simulated sensor responses to different environmental variables and uncertainties to calibrate synthetic sensor models. These are used to bias and noise radiances featuring vegetation up-welling radiance and solar down-welling radiances and evaluate their impact on the retrieval of F using spectral fitting methods approach. First the impact of uncertainty in the radiometric and spectral calibrations is addressed, as well as the effect of different spectral shifts. Then we evaluate the effects of thermally-induced changes in spectral features and sensor response (DRF), as well as non-linearity, and the directional response function of the cosine diffuser.

Results reveal the sensitivity of F retrieval to different instrumental responses. Calibration uncertainties have little effect on the retrieval; however, spectral changes, non-linearity and DRF present strong effects on F retrieval that co-vary with the environmental drivers of the sensor response. The effect of the different phenomena on F retrieval is compared with the impact on the reflectance factors, which results negligible in most of the cases. This suggests that proximal sensing of F requires new and higher quality standards than those accepted in "traditional" proximal sensing dedicated to the quantification of reflectance. Quantification and development of such standards should be prioritized considering the growing interest on F. Inadequate understanding and characterization of instrumentation can lead to spurious results, where instrumental responses to environmental variables are confounded with physiological responses to the same drivers. Uncertainties and biases on F proximal sensing retrievals also jeopardize validation and scaling of F in the context of the up-coming FLEX mission.

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Instrumental characterization, measurements protocols, and retrievals methods in the proximal sensing of sun-induced chlorophyll fluorescence

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Space-based retrievals and up-coming missions such as Earth Explorer of the European Space Agency FLuorescence EXplorer (FLEX) have boosted the growing interest on the proximal sensing of sun-induced chlorophyll fluorescence (F) in. In the last ten years, field spectroradiometers have improved in spectral resolution (Full Width Half Maximum, FWHM ≤ 0.3nm) and signal-to-noise ratio (SNR ~ 1000:1). Still, F can only be measured at very narrow parts of the spectrum and the signal is small. Very precise measurements (spectrally and radiometrically) of radiance (L) and incident irradiance (E) are necessary which adds more complexity to the radiometric measurement procedure. Additionally, to properly interpret the signal also the light history (irradiance) is important. Altogether, this requires properly calibrated and characterized instruments, reliable measurement setups, sophisticated measurement protocols, and robust retrieval methods that exceeds those of classical spectral sampling. For the last four years, many researchers have worked within the framework of an European cooperation in science and technology (COST) action ES1309 to meet the aforementioned challenge by developing innovative optical tools for proximal sensing of ecophysiological processes (OPTIMISE; https://optimise.dcs.aber.ac.uk/). To make this information available, the OPTIMISE community has compiled three papers on instrument characterization (paper 1), measurement setups and protocols (paper 2), and retrieval methods (paper 3). The aim of this work is to provide the scientific community basic guidelines towards a precise measurements of proximal sensing sun-induced chlorophyll fluorescence.

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Litchfield Savanna Supersite – A CEOS Land Process Validation site in northern Australia

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22% of the global land surface are comprised of tropical savannas. Australia's savanna cover
approximately 1.9 million km2 which corresponds to 25% of Australia's land surface or 12% of the
world's savannas. Due to their highly dynamic nature savannas are an important and sensitive
component of the global carbon and water cycle.
The Litchfield Savanna Supersite is located in northern Australia's Top End approx. 80km south of
Darwin in Litchfield National Park. Situated in the mesic tropical savanna the vegetation is
comprised of savanna woodland dominated by Eucalyptus minata /tetrodonta with a grass and low
shrub understorey. Tree height ranges from 15-20m. This makes the area representative for 90% of
Australia's savanna. The site is flat with elevation ranging from 203-228m above sea level over a
5km x 5km area.
Mean annual rainfall is 1420mm, of which 90% falls between December and March. This
pronounced wet / dry season climate induces annual, natural drought conditions. Together with
frequent disturbance through fire (every one to two years) this creates a highly dynamic ecosystem.
Atmospheric conditions at the site range from very clear and very dry in the early dry season to high

concentrations of absorbing aerosols (smoke) in a dry atmosphere in the late dry season. The wet season is typically characterised by very wet atmospheric conditions. As rain events are occurring in intense bursts the number of cloud free days is still relatively high during the wet season.

Due to the site's local and global importance for the carbon and water cycle the Terrestrial Ecosytem Research Network (TERN) installed an eddy covariance flux tower in 2015 to complement existing long-term experiments monitoring canopy and understorey dynamics (leaf area index, leaf fall, leaf litter decomposition). Furthermore, instruments for measuring meteorological conditions and soil moisture profiles have been installed. The installation of a soil moisture sensor grid is planned for 2019.

Vegetation structure at the site has been characterised through a number of airborne and ground based Lidar data captures. Additionally, flora and fauna surveys are undertaken at regular intervals.

A program to regularly capture airborne hyperspectral data coincident (within ±5min) with satellite overpasses has been initiated in 2017. These data have been used for the validation of surface reflectance from Sentinel-2/MSI, Terra/MODIS and Aqua/MODIS. A suitable program for capturing solar induced fluorescence is currently under development.

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Adapting the FLEX Fluorescence retrieval concept from land vegetation to inland water

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The FLEX (FLuorescence EXplorer) satellite mission, under preparation by the European Space Agency (ESA) within the Earth Explorer program, aims to observe the sun-induced chlorophyll fluorescence signal (SIF) emitted by terrestrial plants. The FLuORescence Imaging Spectrometer (FLORIS) aboard of the FLEX satellite is specifically designed to provide radiance observations in high-spectral resolution (0,3 nm) around the O2 bands (687 nm and 760,4 nm), together with a broad spectral coverage from 500 nm to 780 nm (visible-NIR wavelength range). The Sentinel-3 satellite will fly in tandem to FLEX to provide useful information for a proper characterization of the atmosphere with the accuracy required to retrieve the SIF signal. This specific design of FLORIS gives the possibility to spectrally resolve the SIF spectrum in the 670 nm – 780 nm range for land applications. The FLEX mission will observe mainly continental areas and terrestrial vegetation, but there is a growing interest to understand the potential benefits in exploiting FLEX observations to study and monitor inland water bodies (i.e., lakes) and shallow costal waters. In fact, phytoplankton contains chlorophyll pigments able to emit fluorescence signal after solar light stimulation. For this reason, it is interesting to understand whether the FLEX technique developed for the vegetation, such as the Spectral Fitting (SF) method, can be further applied to aquatic ecosystems after a proper adjustment.

In this framework, the aim of this work is to implement and test the SIF retrieval algorithm developed for vegetation applications (Cogliati et al., 2015) to model and fit the SIF signal in water-leaving radiance spectra. The SF approach was initially revised in order to model the atmosphere-water radiation transfer (RT) interactions. To achieve this aim, we coupled the atmospheric RT model MODTRAN with the water RT model Hydrolight. The latter code allows to simulate several water bodies, characterized by different optical and physical/chemical properties. Inland waters are usually parametrized following a four elements model: pure water, bearing chlorophyll particles, Colored Dissolved Organic Matters (CDOM) and Total Suspended Matters (TSM). Radiance and reflectance upwelling spectra generated by the coupled MODTRAN-Hydrolight model, in high-spectral resolution (0,1 cm-1), were convolved to the FLEX and S-3 spectral bands. Starting from this dataset, we applied the SF retrieval method, adapted for aquatic ecosystem, to retrieve the SIF. The results obtained on the simulated dataset show the promising theoretical perspective to use the FLEX technique also on water targets. This preliminary results will be further compared and discussed in regard of real ground-based experimental measurements recently acquired during a number of field campaigns.