Summary

Sun-induced fluorescence (SIF) has been emerged as unique and relatively novel remote sensing (RS) signal in the contemporary era to understand and monitor the terrestrial vegetation activity as well as their structural and functional diversity. The research and applicability potential of SIF has been well recognized by scientists. The SIF signal is emitted from the core of photosynthetic processes and is directly linked to plant photosynthetic activity and plant health conditions. As SIF signal originates from the core of photosynthetic activity, which is an important biochemical process in terrestrial ecosystems that regulates gas exchange between the atmosphere and biosphere, the significance of SIF science is high and is permanently increasing with development of new methods of its retrieval from spectroscopic data and application of new remote sensing platforms and systems to measure SIF from ground, near-atmosphere (UAV, airborne) and space (satellites). The advancement of optical and hyperspectral RS technologies offers currently unique possibilities to capture and estimate SIF signals and reflectances (R) in order to monitor the status of terrestrial vegetation, their phenology, and ecosystem functions. Narrow-band hyperspectral imaging spectrometers are rapidly evolving and provide unique opportunities for monitoring SIF signals at both O_2 absorption bands and R at different wavelengths.

In this PhD research, *HyPlant* airborne imaging spectrometer (the airborne demonstrator of European Space Agency's FLEX FLORIS satellite) has been extensively implemented to estimate, monitor, and model SIF signals at both O_2 absorption bands over heterogeneous peatland and surrounded forest and grasslands ecosystems for the first time. *HyPlant* is a high-performance airborne spectrometer to measure R and SIF developed by Forschungszentrum Jülich, (Germany) in cooperation with SPECIM Spectral Imaging Ltd. (Finland). Most important part of the research conducted within this PhD is based on the HyPlant airborne campaign held in July 2015 over Rzecin peatland located in the western part of Poland.

The PhD is based on the four research papers published in period 2019-2021 in journals with impact factor from 1.53 to 4.85. The structure of the PhD reflects the content of these papers, starts from general introduction to the PhD topic and its objectives and applied methods and ends with summary and conclusions. This PhD thesis is divided into six chapters.

Chapter 1 outlines a general introduction to the PhD dissertation and SIF. The objectives and hypothesis of the thesis have been discussed in this chapter. The origin and types of the SIF signals from plant photosynthetic activity has been also discussed. The *HyPlant* airborne campaign details along with the short description of the applied methods used to verify the research hypothesis have been also described.

Chapter 2 addresses the comprehensive and current state-of-the-art review on Top-of-Canopy (TOC) SIF studies from the ground, UAV, airborne to spaceborne observations. The review focuses on the studies that have been conducted on SIF measurement techniques, retrieval algorithms, modelling, application and validation, incorporating different RS observations platforms and sensor along with their present limitations.

Chapter 3 represents the first airborne SIF maps at both O_2 absorption bands at 687nm and 760nm of the Rzecin peatland and surrounding ecosystems. This chapter also shows the degree of agreement between SIF signals at both O_2 absorption bands and spectral indices which were associated with plant structural and functional traits. It also represents the

sensitivity of the SIF signals with productivity gradient at ecosystem scale and plant community scale.

Chapter 4 is a machine-learning-based methodological model chapter that shows the simulation of SIF signals at 687nm and 760nm in a step-wise approximation manner from simple spectral vegetation indices (NDVI, SR, NDVIre, EVI, PRI) using airborne imaging spectrometric data through fuzzy modelling and data integration techniques. It was shown that the fuzzy modelled approach can accurately approximate the SIF signals at both O_2 absorption bands from vegetation traits as well as can capture the structural and functional diversity of the vegetation at the ecosystem scale.

Chapter 5 represents the importance of reflectance satellite-based vegetation spectroscopic measurements through various spectral indices, in estimations of gross primary productivity (GPP) and net photosynthesis (PsnNet) of tropical ecosystems. It outlines a comparative investigation of different correlation methods (i.e., Pearson product, Spearman rank, and Kendall rank) and supervised machine learning models (i.e., random forest, conditional inference forests, and quantile regression forests) to explore the agreement and possibility of prediction of GPP and PsnNet based on spectral indices, tasselled cap transformations, and reflectances over a mixed ecosystems under tropical seasonal variability.

Chapter 6 provides the synthesis and conclusions of the PhD thesis. The overall conclusion indicates that the developing science about SIF incorporating modern RS technology has emerged and opened new direction advancing the knowledge in terrestrial vegetation and the global carbon cycle, with the development of the ground-based instruments such as FloXbox (JB Hyperspectral Devices GmbH, Germany) and PICCOLO-DOPPIO (The University of Edinburgh, UK), airborne sensors like HyPlant, and upcoming space missions like the Fluorescence Explorer (FLEX) Fluorescence Imaging Spectrometer (FLORIS) of European Space Agency (ESA) satellite, etc.

The PhD results provided the first experimental evidence that through the red (SIF_{687}) and far-red (SIF_{760}) chlorophyll fluorescence signals it is possible to capture the huge spatial heterogeneity of peatland, forest and grassland ecosystems representing different photosynthetic activity, biochemical and structural traits of diversified plant communities and hence to facilitate the assessments of the wide functional diversity of vegetation canopies. Furthermore, it has been observed that the developed fuzzy modelling techniques named SIF_{fuzzy} and $SIF_{fuzzy\text{-}APAR}$ can approximate the original SIF signals at both O_2 absorption bands with high accuracy and also is able to represent the structural and functional diversity of plant canopies. This research has also indicated that the differences in meteorological and environmental conditions have an impact on plant functional activities observed through satellite observed reflectances that significantly differ the prediction process of GPP and PsnNet based on the remote sensing approaches.

Keywords: Sun-induced fluorescence (SIF); Spectral vegetation indices; *HyPlant;* Imaging spectroscopy; Fuzzy modelling; Machine learning; Gross primary productivity (GPP); Peatland; Forest; Grassland.

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Date: 17.11.2021 **Signature**