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Warsaw, 10 January 2022 r.

Review of Doctoral Dissertation

Author: Subhajit Bandopadhyay

Title: Application of ground, airborne and satellite remote sensing techniques to assess the Sun-induced fluorescence and reflectance of different ecosystems

General description

The basis for the implementation of this review was the letter of Prof. Dr. Hab. Eng. Mariusz Sojka, Chairman of Discipline Council of Environmental Engineering, Mining and Energy. The work sent for review was carried out under the supervision of Prof. Dr. Hab. Eng. Radosław Jaszczuk and auxiliary supervisor Dr Anshu Rastogi. It was prepared and presented for evaluation on the basis of four articles, which constitute an integral part of the dissertation. Documentation of the work has been provided in printed and digital form and includes, among others:

1. Doctoral dissertation,
2. Publications included in the doctoral dissertation.

All of included in this thesis manuscripts have been published in journals with an impact factor (IF). These are the following works:

1) Bandopadhyay S., Rastogi A., Juszczak R. 2020. Review of Top-of-Canopy Sun-Induced Fluorescence (SIF) studies from ground, UAV, airborne to spaceborne observations. Sensors, 20, 1144. DOI: https://doi.org/10.3390/s20041144 **(IF=3,576)**
2) Bandopadhyay S., Rastogi A., Rascher U., Rademske P., Schickling A., Cogliati S., Julitta T. et al. 2020. Hyplant-derived sun-induced fluorescence—A new opportunity to disentangle complex vegetation signals from diverse vegetation types. Remote Sensing, 11, 1691. DOI: https://doi.org/10.3390/rs11141691 **(IF 4.848)**
3) Bandopadhyay S., Rastogi A., Cogliati S., Rascher U., Gąbka M., Juszczak R. 2021. Can Vegetation Indices Serve as Proxies for Potential Sun-Induced Fluorescence (SIF)? A Fuzzy Simulation Approach on Airborne Imaging Spectroscopy Data." Remote Sensing 13, 2545. DOI : https://doi.org/10.3390/rs13132545 **(IF 4.848)**
4) Bandopadhyay S., Pal L., Deb Das R. 2021. Predicting gross primary productivity and PsnNet over a mixed ecosystem under tropical seasonal variability: a comparative study

between different machine learning models and correlation-based statistical approaches." Journal of Applied Remote Sensing 15(1), 014523. DOI: https://doi.org/10.1117/1.JRS.15.014523 **(IF 1.53)**

The total IF coming out from the above mentioned scientific papers is 14.772 and the number of points of the Ministry of Science and Higher Education is 340. The PhD student is the first author in all the papers. It can therefore be concluded that her participation in them is significant and entitles his to use them as the basis for awarding a doctoral degree.

The title of the dissertation is well articulated and properly expresses the research aim which is addressed to assess the Sun-induced fluorescence (SIF) and reflectance (R) of different ecosystems through ground, airborne and satellite remote sensing techniques. The dissertation consists of 6 relevant chapters. Chapter 1 is the Introduction, chapter 2, 3,4 and 5 are based on publications mentioned above. Chapter 6 is the synthesis. The dissertation consist 208 pages without Appendix.

Generally, the dissertation is elaborated at very high and international scientific level with very well interesting and valuable results. The text is well written, clear, logical and professionally formulated. The used structures in the text are generally proper and helps the Reader to get enhanced and fast orientation in the topic. The figures, schemes and tables are appropriately chosen and exposed. In overall, the dissertation fulfils the formal request at very good level. Moreover, the Author had used fitting number of high-quality levels of bibliography and correctly quoted them it in this thesis. There is no doubt, that the Author has deepen theoretical and practical knowledge and He is absolutely keen in the investigated problem which was discussed properly in the dissertation.

Doctoral dissertation of Mr. MSc. Subhajit Bandopadhyay

The content of the thesis, its goals, the methods used, and the structure are fully compliant with the requirements for doctoral dissertations and the principles adopted in technical sciences. The main topic of the work is about the possibility to assess the sun-induced fluorescence (SIF) and reflectance (R) of different ecosystems through ground, airborne and satellite remote sensing techniques. It should be emphasized that the subject of the work is very actual, as remotely observation and accurate quantification of photosynthetic activity of terrestrial vegetation are unresolved problem and often the results of estimations are very biased. The SIF seems to be a

tool thanks to which it will be possible to more closely monitor the photosynthesis process. Therefore, it should be recognized that the subject taken up by the PhD student is not only topical or experimental, but also of great utilitarian importance.

In the "Introduction" section a lot of space has been dedicated to the full characteristics of the SIF technique. The PhD student indicates that vegetation traits based on the spectral indices are not sensitive enough to monitor the short-term dynamics of vegetation functionalities because the changes in photosynthetic process under different different environmental conditions and/or stress factors is not reflected enough by such spectral indices. However, SIF signal is sensitive enough to monitoring even minor changes of plant physiological conditions, which can be easily detectable by the modern RS technologies in a real-time manner.

On the basis of a literature reviewed by the PhD student it was shown that the use of hyperspectral reflectance measurements can help to get better understanding of the ecological patterns of peatland and other homogeneous surfaces like forests, grasslands and croplands. The PhD students however pointed that, SIF signals reemitted by photosynthetic machinery, which can be obtained through narrow-band hyperspectral imaging spectrometers, have been not used yet to monitor the heterogeneous ecosystems, such peatlands. This confirms that the implementation of narrow band SIF signals on airborne imaging spectroscopy is very up-to-date.

The analysis of the current state of theoretical knowledge and practical solutions carried out by the PhD student allowed him to set the following goals:

1) Evaluation the current potential application of SIF, conducting in-depth survey, review, and interpretation of existing SIF studies based on the ground, airborne, UAV, and spaceborne observations, in order to identify the current knowledge gap, associated limitations and challenges of existing SIF studies.

2) Retrieving the first airborne SIF maps at both oxygen absorption bands (SIF_{760} and SIF_{687}) of heterogeneous peatland and surrounding ecosystems. Also, exploration and analysis of SIF_{760} and SIF_{687} signals obtained from different managed and natural ecosystems over homogeneous (forest, grassland, etc.) as well as from heterogeneous (peatland) ecosystems using airborne imaging spectroscopic data.

3) Understanding and comparison the inter-relationship between spectral vegetation indices and vegetation biophysical parameters with SIF760 and SIF687 signals over peatland and surrounding ecosystems from plant community scale to ecosystem scale.

4) Developing a proxy of SIF signals from simple spectral vegetation indices using airborne imaging spectroscopic data. Furthermore, step-wise approximation of the novel SIF_{760} and SIF_{687} signals from different vegetation traits in terms of spectral indices using the fuzzy model and airborne spectrometry.

5) Understanding the seasonal uncertainties in GPP and PsnNet prediction process from satellite derived reflectance spectra as well as to compare and understand the interlink with several spectral vegetation indices and tasselled cap transformations, through the implementation of different correlation methods (i.e. Pearson, Spearman, and Kendall rank) as well as through different supervised machine learning models (i.e. Random forest-RF, Conditional inference forests- cForest, and Quantile regression forests- QRF).

In the opinion of the Reviewer, these aims were generally set correctly. After a properly conducted "Introduction", there is no doubt that the aims set in the work are justified from a scientific point of view. I only have doubts about the first aim, which will be discussed later in the review.

Based on the analysis of research issues, the following research hypothesis were formulated:

1) Novel SIF signals have a direct agreement with vegetation traits, however, this agreement may vary from plant community scale to ecosystem scale.
2) Vegetation traits can be used to approximate SIF at both oxygen absorption bands and can also replicate SIF signals over different ecosystems in agreement with the original (measured) SIF.

In the "Materials and Methods" chapter, the doctoral student provides information about the location of the experiments. Most of the research was done over the peatland of Rzecin (POLWET) in the western part of Poland. At this point, I miss information about why this particular habitat was chosen as the research object. The author does refer to specific articles for detailed information, but it is worth adding some information about the uniqueness of this place?

It should be emphasised that the research programme itself is very broad. The Rzecin moorland in Poland was chosen as the main research area. This includes airborne hyperspectral

measurements. For this purpose, an airborne campaign was organised using HyPlant. This campaign was funded by the European Space Agency (ESA) under the Fluorescence Explorer mission FLEX-EU, the European Facility for Airborne Research (EUFAR) and the Cost Action OPTIMISE (ES1903). The hyperspectral field measurements were performed on the same day and time as the airborne measurements. Two HR4000 spectrometers (OceanOptics, Largo, FL, USA) covering different wavelength ranges were used to estimate TOC reflectance and SIF. In addition, Leaf Area Index (LAI), photosynthetically active radiation (PAR), and fraction of photosynthetically active radiation absorbed (fAPAR) were measured on the same day and at the same locations. The Ph.D. student calculated several spectral vegetation indices from the HyPlant DUAL channel module and from the hyperspectroradiometers used for the ground measurements, representing different properties of the vegetation in terms of plant physiology, chemical composition, structure, xanthophyll pigments, and water content. The Spectral Fitting Method (SFM) was used by PhD student to calculate the far-red SIF (SIF760) and red SIF (SIF687) maps over Rzecin.

The application of supervised machine learning techniques (ML) to satellite-based spectral indices, the transformation of tassel caps for GPP, and the PsnNet prediction process was also a part of this work. Based on these results, three ML models (Random Forest, Conditional Inference Forests, and Quantile Regression Forests) were compared to identify and investigate the prediction process of GPP and PsnNet under the Indian seasonal variations from different VIs, spectral bands, and tasselled cap transforms using MODIS and Landsat 8 OLI data. It should be noted that the research was conducted in collaboration with a very broad team of specialists from different countries, which is also reflected in the list of co-authors of each publication.

Regarding the results of the work, it should be noted that the student did not decide to include in the thesis a description of the results obtained and their discussion. This part of the work is found only in individual articles. However, in these articles the doctoral student has shown that the adopted research objective has been consistently pursued. The attached documentation, which the doctoral student presents here, has been carefully prepared and the statistical methods used in the research are correct.

Chapter 3 provides information on the detection of red (SIF687) and red (SIF760) chlorophyll fluorescence signals in a heterogeneous peatland ecosystem with high and complex spectral

diversity. Despite these characteristics of this ecosystem, the Ph.D. student demonstrated that the HyPlant SIF sensor is capable of successfully detecting signals from the surface of the complex vegetation of a peatland. However, these results were only obtained on one day during the summer. The PhD student also found that the airborne SIF signals can also be used to monitor the structural and functional diversity of the peatland and surrounding ecosystems such as forests, grasslands, etc. from the plant community level to the ecosystem level. Simultaneous measurement of fAPAR, LAI, and VIs along with SIF signals was also conducted on the day of the aerial photography campaign. This helps to relate the SIF signals in both oxygen absorption bands to biochemical, structural and functional characteristics of the vegetation in the peatland ecosystem. The author also observed a link between the SIF signals and the VIs that regulate the structural and functional characteristics of the peatland vegetation, as well as the environmental and meteorological dependence of the emitted SIF signals and the reflections over the peatland vegetation.

In Chapter 4, the results of approximating the SIF signals from simple VIs using HyPlant airborne spectroscopy data were shown. According to the PhD student, the proposed SIFfuzzy and SIFfuzzy- APAR can effectively approximate and replicate not only the SIF760 signal, but also the (weaker) SIF687 signal. As a result, the ability of approximation and replication of reflectance-based vegetation features by SIF760 and SIF687 was confirmed. The author proved that the proposed method of fuzzy simulation can be applied to study sites other than peatland ecosystem and also at global scale. The fuzzy simulation was applied to the HyPlant derived SVIs by a graduate student. The method can also be applied to space-based SVIs (EVI or NDVI) derived from commonly used satellite datasets such as Landsat 8, Sentinel-2, or MODIS.

In Chapter 5, the PhD student highlighted and compared different correlation methods (i.e. Pearson, Spearman rank, Kendall rank) and different ML models (RF, cForest, QRF) to investigate the agreement and contribution of variables such as bands, spectral indices, and tassel-hat transforms to predict GPP and PsnNet in the presence of seasonal and inter-annual variability. The author found that under both seasonal conditions, a higher proportion of PsnNet is associated with high productivity. He also proved that NIR-based spectral indices such as NDVI, IPVI, SLAVI, WDRVI or CIgreen have a strong correlation with GPP and PsnNet under both seasonal conditions. These results also show that there is a relationship between NIR and crop productivity. The underlying causes and uncertainties associated with the GPP and PsnNet estimation procedure were also discussed in this paper. In general, these results can improve

the accurate estimation of carbon cycle and terrestrial productivity, which seems to be very important not only for farmers but also for protected area management.

The results described above were summarized by the doctoral student in Chapter 6, "Synthesis." The well-documented summary contained in this chapter fully meets the stated objectives of the thesis. In formulating this summary, the doctoral student has exercised both criticism and due caution. However, apart from this part, there are no rigorous conclusions to the end of the dissertation. I believe that the conclusions should nevertheless be drawn after the synthesis. It does not matter that they are in individual articles. There were also goals in individual articles and the doctoral student rightly reflected them in the dissertation.

Dissertation of Mr. MSc. Subhajit Bandopadhyay has been prepared in an editorially correct and careful manner and meets the formal and substantive requirements for a doctoral dissertation. As mentioned in the introduction of this review - an integral part of the dissertation are 4 articles published in international scientific journals with an impact factor (IF) and certainly peer reviewed by high calibre experts. In my opinion, the material presented in these articles also meets the formal and substantive requirements for the award of the doctoral degree. Dissertation of Mr. MSc. Subhajit Bandopadhyay brings new cognitive and utilitarian elements that enrich the knowledge in the field of the possibility of monitoring plant communities by sun-induced fluorescence. This work is a closed research loop from concept to careful site selection, appropriate methods, and discussion of the author's own results and their confrontation with the views of other authors.

Critical remarks and questions:

1) The doctoral student uses a lot of abbreviations. Abbreviating the names of species or habitats goes too far and often results in having to resort to describing the abbreviations.

2) I am not sure if SIF is a new signal? The technique of its measurements may be new, but the signal itself is as old as photosynthesis.

3) Chapter 1 is incorrectly divided into subchapters. Subchapter "Introduction" should be numbered 1.1, not 1. Subchapter "1.1 Significance of the Work in the Present Era" should be numbered 1.2. etc. In the current version there are two sections numbered "2" - subchapter 2 "Materials and Methods" and chapter 2 "Review of Top-of-Canopy Sun-induced Fluorescence (SIF) studies from ground, UAV, airborne to spaceborne observations".

4) The first goal of the thesis ("Evaluate the current application potential of SIF, conduct an in-depth investigation, review and interpretation of existing SIF studies...") should not, in my opinion, be the goal of the thesis per se. Such information should be included in the literature review. It was a good idea to start the work cycle with an overview, but it should be given the role of an introduction to the work.

5) As mentioned in the main body of this review, the PhD student provides information about the location of the experiments in the "Materials and Methods" chapter. At this point, more information should be included about why this particular habitat was chosen as the research subject. While the author refers to specific articles for detailed information, it is worth adding some information about the uniqueness of this site.

6) The PhD student explained that fAPAR was measured using the BF5 sensor (DELTA -T, UK). However, the BF5 sensor can only be used for additional measurements PAR above the plants, not below them. For this purpose (as well as for measurements of LAI) the 1m probe must be used.

7) What does "post-agricultural land (PG)" mean (Fig. 3. Chapter 3)? All grassland is used for agricultural purposes. Is this agricultural fallow land?

8) What is the difference between semi-mowed Arrhenatherion grass and mowed Arrhenatherion grass (Appendix 1, Chapter 3)?

9) In general, graduate students should use the appropriate phytosociological names when describing plant communities in Chapters 3 and 4. There are no communities like semi-natural forests with Pinus sylvestris. Deciduous forest is a broad term because riparian forests should also be included in this group, but the PhD students separated these two communities. A similar mistake was made with sedge and rush vegetation. In addition, alder forest (abbreviation AF) is definitely a forest community (as is the aforementioned riparian forest) and not bog vegetation.

10) The measurements presented in Chapter 3 were made on one day (July 15). Can the conclusions obtained be extrapolated to other seasons (early spring, late summer, or fall)?

11) HyPlant measurements were made at two times of the day - morning and early afternoon. Is the latter time period not biassed due to the high probability of photoinhibition in plants?

12) Is SunScan a good tool for measuring fAPAR and LAI in mosses? Could the LAI values obtained be underestimated in this group of plants?

13) On page 170, the PhD student uses the expressions: Forest Ecosystems and Moss Ecosystems. However, the word "ecosystem" is very broad because it means biocenosis together with a biotope. In the case of this sentence, communities are the better word.

14) Although the student could not elaborate the results separately in the dissertation (which would have its advantages), the omission of the conclusions in the last chapter should be considered a mistake.

Conclusions

Dissertation of Mr. MSc. Subhajit Bandopadhyay is a complete scientific study based on a multi-layered research where data has been collected and processed using the latest methods. This work has both cognitive and practical value. The material collected and its critical discussion demonstrate the doctoral student's skills in using various research methods and statistical procedures. The doctoral student has demonstrated substantive knowledge and a good knowledge of the literature in formulating the objectives of the thesis and the conclusions resulting from the experiments. There is no doubt that the doctoral student is a talented and independent researcher, and the research she has conducted is at a level that does not deviate from current European standards.

PhD thesis of Mr. MSc. Subhajit Bandopadhyay meets all the requirements for doctoral dissertations in accordance with the Act of 20 July 2018 Law on Higher Education and Science. Considering my positive assessment, I apply to Prof. Dr. Hab. Eng. Mariusz Sojka, Chairman of Discipline Council of Environmental Engineering, Mining and Energy for admission to M.Sc. to the next stages of the doctoral dissertation.

Warsaw, 10 January 2022