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Wydział Geografii i Studiów Regionalnych
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Review of the doctoral dissertation

prepared by M.Sc. Subhajit Bandopadhyay
titled: **Application of ground, airborne and satellite remote sensing techniques to assess the Sun-induced fluorescence and reflectance of different ecosystems**
proceed at the Poznań University of Life Sciences Faculty of Environmental Engineering and Mechanical Engineering, under the supervision of Prof. Dr. hab. Radosław Juszczak and Dr. hab. Anshu Rastogi, Prof. UPP

The dissertation consists of 208 pages of compact text based on four papers published in prestigious international journals (the total Impact Factor is: 14.802). The manuscript is arranged as follows:

- Title page, affiliations of supervisors and the thesis committee, dedication to the PhD student's parents, acknowledgments, list of contents of the doctoral dissertation, list of papers constituting the doctoral dissertation, description of the PhD student's contribution to the publications constituting the basis of the thesis, summaries in English and Polish, as well as a list of used abbreviations.
- Chapter I: *General Introduction* consists of two chapters: *1. Introduction*; 2. *Materials and Method*. The *Introduction* covers almost six pages of typescript, in which the Author introduces readers to the topic of the dissertation, presenting important information in the field of chlorophyll fluorescence, hyperspectral remote sensing, solutions in environmental modeling, which supports terrestrial ecosystem monitoring. Range of the thesis, its goals and outline are presented in the form of sub-chapters. The second part of the *General Introduction* includes almost eight pages of *Materials and Method*, where the Author described the research area, which is located near Rzecin village (Szamotuły district) where airborne and field campaigns were conducted in frame of the HyPlant project, which was financed by the European Space Agency (ESA) as part of the Fluorescence Explorer (FLEX-EU) mission, as well as the activities of the European Facility for Airborne Research (EUFAR) and Cost Action OPTIMISE (ES1903). In the frame of the field activities, hyperspectral characteristics (0.2-1.0 nm spectral resolution) were obtained, as well as measurements of indices: leaf area index (LAI), accumulated photosynthetically active radiation (APAR), and meteorological parameters, which allowed to verify proposed models. The spectral characteristics allowed to calculate remote sensing indices of

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vegetation in the field of photosynthetically active pigments, plant stress, and biomass content. Solar-induced fluorescence analyzes were performed using Spectral Fitting Method modeling, fuzzy logic simulations and supervised machine learning. This part of the work is richly documented because Author based on 30 international publications, 17 of which were published in the last five years.

- Chapter II: *Review of Top-of-Canopy Sun-induced Fluorescence (SIF) studies from ground, UAV, airborne to spaceborne observations* is a review paper published by the PhD student and his supervisors (Bandopadhyay S., Rastogi A., Juszczak R., 2020, DOI: 10.3390/s20041144) in *Sensors* (MDPI, IF = 3.576, Q1/Q2). The article presents the latest achievements in the field of doctoral dissertation in a methodical way, the quality of the article has been appreciated by readers, because despite the fact that it was published in February 2020, according to the Web of Science, it was cited 14 times (as of 06.12.2021).
- Chapter III: *Hyplant-Derived Sun-induced fluorescence – A new opportunity to disentangle complex vegetation signals from diverse vegetation types* is a team-work prepared by 23 authors (Bandopadhyay S., Rastogi A., Rascher U., Rademske P., Schickling A., Cogliati S., Julitta T., Mac Arthur A., Hueni A., Tomelleri E., Celesti M., Burkart A., Strozecki M., Sakowska K., Gabka M., Rosadzinski S., Sojka M., Iordache, M.-D., Reusen I., van der Tol Ch., Damm A., Schuettemeyer D., Juszczak R.) representing 14 leading research units in Europe. This article was published in the Remote Sensing (MDPI, IF = 4.848, Q1/Q2). Since publication date (17.07.2019) paper was 10 times cited in journals indexing by the Web of Science. Personally, I perceive this paper very positively, because the PhD student is the first author, and the co-supervisor is the second on the authors' list, which means that the main framework of the article was given by the PhD student unit, but so many co-authors representing core European units, who allowed the PhD student to obtain the right research perspective on the newest methods, as well as development and verification of the obtained results. The fact that the research area is located in Poland also plays a significant role, which allows to promote Polish scientific achievements and create reference databases for Polish achievements. The paper identified spatial relationships between SIF and vegetation indices (VIs) from large scale vegetation ecosystems to small scale peatland plant communities, e.g., correlations between SIF and indices, biomass of vascular plants (associated with higher Leaf Area Index (LAI)). SIF signals, especially SIF760 were strongly associated with the functional diversity of the peatland vegetation. It allowed to create the first airborne SIF maps at both O2 absorption bands at 687 nm and 760 nm of the Rzecin peatland and surrounding ecosystems. At the peatland area, higher values of SIF760 were associated with plant communities of high perennials, whereas, lower values of SIF760 indicated peatland patches dominated by *Sphagnum.* In general, SIF760 reflected the productivity gradient on the fen peatland, from *Sphagnum* dominated

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patches with the lowest SIF and fAPAR values indicating lowest productivity to the *Carex* dominated patches with the highest SIF and fAPAR indicating highest productivity. Authors indicated that a diversity in SIF maps reflects the diversity in their photosynthetic activity which may correspond to photosynthetising biomass of vascular plants.

- Chapter IV: *Can Vegetation Indices Serve as Proxies for Potential Sun-Induced Fluorescence (SIF)? A Fuzzy Simulation Approach on Airborne Imaging Spectroscopy Data* is another article published in the Remote Sensing. The PhD student is the first author, and supervisors and three more co-authors complete the authors' list (Bandopadhyay S., Rastogi A., Cogliati S., Rascher U., Gabka M., Juszczak R.). Due to the publication date (29.06.2021), this article has not yet been cited by journals indexing by the Web of Science, but it is an important contribution presenting a methodological proposal of a new model based on machine learning and on the spectral features of the hyperspectral image (remote sensing vegetation indices), which has a great importance because images enable an identification of individual species and communities, which allows to differentiate an individual approach to different ecosystems, taking into account the phase of vegetative development. Authors tested a proxy for red and far-red sun-induced fluorescence (SIF). Fuzzy logic modelling approach and combinations of spectral vegetation indices (i.e. SR, NDVI, EVI, NDVIre, PRI) allowed to approximate the potential SIF signals at 760 nm and 687 nm. Authors confirmed that the model allows to 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. The agreement between modelled SIF_{fuzzy} and actual SIF airborne retrievals expressed by R^2 ranged from 0.38 to 0.69 for SIF760 and from 0.85 to 0.92 for SIF687. Whereas, the inclusion of APAR improved the R^2 value between $SIF_{fuzzy\text{-}APAR}$ and actual SIF.
- Chapter V: *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* is a paper, which was published in Journal of Applied Remote Sensing (IF = 1.53, Q4) by the team of Bandopadhyay S., Pal L. and Das R.D. Due to the publication date (21.03.2021), the paper has not any citation on the Web of Science. The article confirms the importance of reflectance and its various spectral indices to estimate of gross primary productivity (GPP) and net photosynthesis (PsnNet). For this goal tropical ecosystems, MODIS and Landsat images, supervised machine learning models (i.e. Random Forest, Conditional Inference ForestscForest, and Quantile Regression Forests) and statistical metrices (i.e. Pearson product, Spearman rank, and Kendall rank) were used. It was also confirmed that NIR-based spectral indices offered the best agreements and statistically significant ($p<0.001$) with GPP/PsnNet (coefficients oscillated from 0.44 to 0.85 depending on used regression

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models). It is an important contribution confirming an applicability and universality of the developed solutions.

- Chapter VI: *Synthesis* consists of a three-page description of the achievements of the dissertation.
- Appendix 1: Statements of co-authors on their percentage contribution to publications.
- Appendix 2: Curriculum Vitae and summary of scientific achievements.

Assessment of the doctoral dissertation

The Author undertook the ambitious task of modeling spectral properties of plants analysing a heterogeneous environment, for this purpose he used well-planned international project, which allowed to acquire a wide set of original airborne campaign, as well as reference – ground data obtained during field campaigns accompanying flight imaging. It allowed to propose an interesting set of modelling based on machine learning algorithms. The result of this work, in which leading experts in the field of research were involved, is a very interesting study, considering the modeling of biometric parameters of plants and their spectral properties. The usefulness of modeling with machine learning algorithms has been confirmed on the basis of research conducted at the ground and airborne level. The obtained results were positively verified on the basis of satellite data from another – tropical ecosystem. In my opinion, the achievements constitute a basis for an automation of the process of acquiring data on the state of heterogeneous ecosystems from hyperspectral images, and after placing the planned FLEX mission especially in connection with the Sentinel-2 and 3 data.

The work is easy to read and understand, it is also the result of the publication of articles in leading journals, where the team of professional editors (technical and language) took care of the high quality of the published papers.

The work brings many new outcomes, which are a combination of plant physiology and hyperspectral remote sensing. These are pioneering works in Poland and are a base for the planned FLEX satellite mission in Europe. The obtained results are extremely important for the monitoring of large areas and open up great opportunities for the practical application of this type of modeling not only in scientific work, but above all in agriculture, plant and animal ecology (food base analysis).

Personally, I have a very positive opinion of the reviewed dissertation, because it is one of the pioneering doctoral theses in this field in Poland. The Author collected a very rich, original documentation material, it was thoroughly analyzed, appropriate procedures were applied and the Author proposed his own original solutions that allowed to achieve intended goals. They should be developed in conjunction with the classification of hyperspectral images,

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which will be the application contribution of remote sensing to modeling the natural environment.

The issue that I would like to discuss during the public defense is the reproducibility of the results obtained in relation to plant changes caused by phenological phases, because the maturation process of individual species is different, so, the spatial changes depends on heterogeneity of species and agrotechnical cultivation, including mowing, which significantly changes the spectral characteristics of the ecosystem.

Author focused on field and HyPlant airborne campaigns (six flight lines) to estimate, monitor, and model Sun-induced fluorescence (SIF) over heterogeneous peatland and surrounded forest and grasslands ecosystems. The research area is located near Rzecin village for 2nd and 3rd papers, and a tropical ecosystem and satellite data for the 4th paper. The acquired results were a base of three papers, additionally the first paper creates a general introduction to the topic, e.g., origin and types of the SIF signals, current state-of-the-art review on Top-of-Canopy (TOC) SIF studies from the ground, UAV, airborne to spaceborne observations, retrieval algorithms, modelling, application and validation, incorporating different remote sensing observation sensors, and their present limitations.

Conclusion with justification regarding the fulfillment of the conditions specified in the law requirements by the reviewed doctoral dissertation

Considering the individual elements of the doctoral dissertation presented for evaluation, MSc. Subhajit Bandopadhyay, who prepared his doctoral dissertation titled: *Application of ground, airborne and satellite remote sensing techniques to assess the Sun-induced fluorescence and reflectance of different ecosystems*, demonstrated above-standard knowledge of data processing, correctly designed procedures for data evaluation, and the obtained results were correctly verified with the available literature on the research topic. I am sure that it is methodically very valuable work for semi-automatic ecosystem mapping on hyperspectral data (currently airborne data, but soon on FLEX satellite data). Moreover, in the presented dissertation, the formal requirements for doctoral dissertations were met, namely: a) the doctoral dissertation presents the Autor's general theoretical knowledge in the discipline, which was confirmed by very-well cited paper #1 and discussions of achieved results in other published papers, b) Author confirmed his great ability to conduct scientific work independently, it was confirmed by all published manuscripts, where the PhD student was the first author integrating distinguish co-authors, who are European leaders in the research topic, c) the PhD student presented a proper methodological solution to the original scientific problem, which was correctly presented highlighting a broader background of theoretical knowledge; d) the PhD student has demonstrated an ability to organize team-work conducting independent

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research on the newest data and solutions and applied in practice advanced tools that led him to a positive verification of the set goals.

I believe that the work is outstanding and a procedure for a PhD award should be undertaken. I really appreciate that the papers have been published in prestigious journals and they are widely available promoting Polish input to the science.

According to the relevant documents on the law on higher education and science (Journal of Laws No. 2021, item. 478 of July 20, 2018, as amended), I fully support the continuation doctoral procedure to the next stages of the public defense.

Yours sincerely

B Zagajewski

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