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PhD thesis of Mr Pouya Ghezel Ayagh

Titled: **Assessing selected environmental properties of peatlands on a large spatial scale using the remote sensing tools and datasets**

Doctoral thesis prepared under the supervision of Dr hab. Mateusz Grygoruk, prof. SGGW Centre for Climate Research

This doctoral dissertation was prepared on the bases of three peer-reviewed and thematically linked scientific articles: The order of the articles matters. The presented research and achievements come from the methodological development of the applications of Vertical Displacement -VD to the ecological assessment tool and the application of the carbon emission estimates.

Article1. **Ghezelayagh, P.**, Oleszczuk, R., Stachowicz, M., Eini, M. R., Kamocki, A., Banaszuk, P., & Grygoruk, M. (2024). Developing a remote-sensing-based indicator for peat soil vertical displacement. A case study in the Biebrza Valley, Poland. *Ecological Indicators*, 166, 112305 (IF = 7.4; MeiN = 200). https://doi.org/10.1016/j.ecolind.2024.112305 focuses on the development and rigorous ground-based validation of the InSAR-based remote sensing methodology, establishing a reliable indicator for detecting peat soil vertical displacement (VD).

Paper2 : **Ghezelayagh, P.**, Eini, M. R., & Grygoruk, M. (2025). Assessing carbon accumulation through peat vertical displacement: The influence of climate and land use across diverse peatland characteristics. *Science of the Total Environment*, 958, 178132 (IF = 9.3 (Scopus); MeiN = 200).
https://doi.org/10.1016/j.scitotenv.2024.178132

Paper 2 describes the regional and local drivers of peatland degradation, using Vertical Displacement (VD) as a proxy for ecosystem health to separate the impacts of anthropogenic drainage from climate change

Paper3: **Ghezelayagh, P.**, Kamocki, A., Banaszuk, P., & Grygoruk, M. (2025). Towards a remote sensing-based assessment of carbon emissions from peatlands. *Scientific Reports*,15, 34175 (IF = 3.9; MeiN = 140 https://doi.org/10.1038/s41598-025-15293-1

Presents the elaboration of carbon emissions by translating physical subsidence into biogeochemical carbon fluxes.

The research was conducted in northeastern Poland, where three representative peatland complexes were selected to encompass a gradient of peatland conditions, ranging from an almost undisturbed system to heavily degraded sites. The Rospuda Valley served as the reference site because it has remained largely unaffected by drainage and intensive land-use change, enabling the separation of climate-driven effects on peatland dynamics from those caused by anthropogenic disturbances. The other study areas, Biebrza Valley and Bagno Wizna, represent progressively more degraded peatlands subjected to extensive drainage. These ecosystems function as natural water reservoirs characterized by contrasting hydrological regimes and varying degrees of ecological disturbance, providing the research for assessing vertical peat movement as an indicator of peatland degradation.

Peatlands are among the ecosystems most vulnerable to climate change. Variations in temperature and precipitation alter groundwater levels, accelerating peat oxidation, subsidence, and the gradual degradation of these valuable ecosystems. Given their crucial ecological functions, including carbon sequestration, water retention, and biodiversity conservation, research on peatlands is of exceptional importance.

The PhD candidate therefore undertook a scientifically challenging and highly relevant research topic. The research on Vertical Displacement has been located in peatlands at the Biebrza valley. Known from the literature that the disappearance of peat soils is particularly evident in peatlands in the Middle Basin of the Biebrza Valley. Soils have been deeply drained with highly decomposed peats. Field observations indicated that the peat soils are estimated to be getting shallower at a 1.0–2.0 cm/year rate, a loss of more than 100 cm of peat has been recorded compared to the 1960 -70 .

The main objective of the dissertation is to investigate the potential of satellite remote sensing for assessing peatland environmental properties over large spatial scales and to develop an indicator based on vertical displacement (VD) for monitoring peatland degradation.

The central hypothesis assumes that satellite radar interferometry (InSAR), when integrated with complementary geospatial datasets, can provide a reliable indicator of peatland vertical displacement, even in seasonally vegetated peatland environments.

To investigate vertical displacement, the PhD candidate employed Interferometric Synthetic Aperture Radar (InSAR), a powerful technique capable of measuring surface deformation with millimetre-level precision (Rosen et al., 2000; Osmanoğlu et al., 2016). InSAR utilizes two or more Synthetic Aperture Radar (SAR) images acquired over the same area to derive information on surface topography and deformation (Lu et al., 2007). By comparing the phase of radar signals recorded during successive satellite acquisitions, InSAR can detect subtle changes in surface elevation and monitor ground movements associated with peat degradation as well as restoration processes.

The amplitude (intensity) of a SAR image is primarily controlled by terrain slope, surface roughness, and the dielectric properties of the observed surface, whereas the phase is mainly determined by the distance between the satellite antenna and ground targets. It is this phase information that enables the detection of minute vertical surface movements.

The overarching objective of the study is therefore to overcome the limitations of applying InSAR in peatland environments by integrating radar interferometry with complementary geospatial datasets. This integrated framework is intended to generate spatially continuous maps of peatland deformation, carbon loss, and carbon emissions, thereby providing valuable information for researchers and policymakers involved in peatland conservation and restoration. To accomplish this objective, the research was divided into three interconnected tasks, each representing a successive stage in the upscaling framework.

Hypothesis 1 assumes that the high revisit frequency of the Sentinel-1 mission, combined with the selection of interferometric image pairs acquired during periods of high coherence (primarily late winter and early spring), makes it possible to generate a stable interferometric phase signal. This signal is expected to correlate strongly with in situ measurements of peat surface displacement.

Furthermore, after calibration using field observations, the InSAR-derived estimates of water-level changes within wetlands are expected to enable accurate quantification of changes in water storage, thereby improving hydrological modelling and enhancing predictions of future flood events in wetland ecosystems.

Hypothesis 2 states that peatland vertical displacement can serve as an effective indicator of peatland health, whereby surface uplift reflects peat accumulation and ecosystem recovery, whereas subsidence indicates peat degradation. In degraded peatlands, drainage induces peat oxidation and shrinkage, resulting in downward surface movement. Consequently, vertical displacement represents a meaningful proxy for evaluating peatland condition and ecosystem health.

Hypothesis 3 proposes that remotely sensed subsidence rates can serve as a surrogate for peatland carbon emissions when combined with the oxidation component of subsidence and spatial information on peat bulk density (BD) and soil organic carbon (SOC) content.

This hypothesis assumes that, by quantifying the oxidation fraction (α) of total subsidence and integrating it with spatially continuous maps of subsidence, peat bulk density, and soil organic carbon content, it is possible to estimate spatially distributed carbon emission fluxes from peatlands. In this way, the PhD candidate transforms measurements of physical vertical displacement into quantitative estimates of biogeochemical carbon loss, enabling regional-scale assessment of peatland carbon emissions.

The PhD candidate used the InSAR products processed by ASF DAAC HyP3 applying the GAMMA software based on the ESA processed Sentinel-1 datasets to calculate peat vertical displacement and evaluated the results with measurements observed from ground-based field surveys and set the research in the Biebrza Valley, covering seasonal-annual period from April 2015 to April 2022. Peat subsidence was measured manually using PVC piezometers of the length exceeding the depth of peat. The piezometers were set in peat soil throughout the observation period. Peat thickness in locations of piezometers varied between 2.0 m and 4.5 m. Subsidence was noted in field measurements of a variable distance from the top of the piezometer to the ground elevation. The measurements were done in approximately 10-day intervals in 11 monitoring locations placed in the Upper and the Middle Basin of the Biebrza Valley. In total, the 337 data records of peat vertical displacement from the period 11/5/2009 to 5/23/2022 were obtained.

The peatland Vertical Displacement described in Paper 1 has been used by PhD candidate for net carbon accumulation, representing the integrated balance between carbon gains and losses. Positive VD values indicate peat accumulation and ecosystem stability, whereas negative VD values reflect subsidence associated with peat degradation and carbon loss. The PhD candidate compared VD across three contrasting peat lands: drained peatlands in Wizna, a mosaic of drained and semi-natural peatlands in Biebrza Valley, and undrained peatlands in Rospuda Valley.

These findings he published in Paper 2. The comparison between Wizna and Rospuda showed that drainage accelerates peatland subsidence by up to 66.7%, and shows how land use change drives peatland degradation and VD became an indicator of this degradation. Positive VD reflects active peat formation and net carbon accumulation, whereas negative VD signifies peat degradation and net carbon loss.

The final methodological contribution of this thesis is the development of Remote Sensing approach to estimate carbon emissions from peatlands. The applied by the PhD candidate methodology translates physical VD into estimates of biogeochemical carbon emissions by exploring the relationship between C emission and peat subsidence.

By incorporating the subsidence rate (Δh_s), the oxidation component (α), and peat properties (C_v), including bulk density (ρ_{peat}) and soil organic carbon (SOC) content (fOC), PhD candidate estimated carbon (C) emissions from peatlands.

This approach has been based on the principles of the POXAPS (Peat OXidation And Permanent Shrinkage) model, which separates total peat subsidence into contributions from peat oxidation and permanent shrinkage (Hayati et al., 2022; Hoyt et al., 2020). The model also describes how the decomposition of peat organic matter is linked to CO_2 emissions (Dahdal, 2011; Wösten et al., 1997).

Conclusions

The thesis addresses a highly relevant scientific and environmental problem. Peatland degradation and its contribution to greenhouse gas emissions represent an important research topic with significant implications for climate change mitigation and ecosystem management.

The PhD candidate established a novel methodology by applying the InSAR approach to detect vertical displacement (VD) in peatlands. To the best of my knowledge, this is the first time that such a method has been applied to peatlands in Poland.

The PhD candidate demonstrated, for the first time, that increasing peatland drainage is associated with increased land subsidence. The results obtained indicate that vertical displacement (VD) has the potential to serve as an indicator of peatland health.

However, the thesis does not sufficiently explain what is meant by the term *peatland health*. The candidate should have more clearly defined the conditions encompassed by this concept, such as hydrological status (moisture conditions), vegetation development, and other ecological characteristics. Incorporating these aspects into the research conducted over the course of the PhD study would have strengthened the interpretation of VD as an indicator of peatland health.

I also could not find a clear definition of the term **"degradation"** as used in this thesis. It would be helpful to explain what is meant by degradation in this context and support the definition with evidence, such as observed changes in soil moisture and vegetation deterioration.

By converting peat subsidence into carbon loss and proposing remote sensing–based methods to derive the required parameters, the PhD candidate presents a methodology for estimating peatland carbon emissions in the Biebrza Valley. The candidate estimated an annual peat volume loss ranging from 8.3 to 12.8 million m^3, highlighting the substantial degradation of peat soils in the study area. This corresponds to a minimum cumulative peat loss of 58.1 million m^3 over the period from 2015 to 2022.

The results obtained by the PhD candidate are consistent with findings from field observation–based studies conducted at numerous sites across Europe (Dawson et al., 2010; Gąsowska et al., 2019), North America (Silins and Rothwell, 1998; Snyder, 2005), and New Zealand (Schipper and McLeod, 2002). This agreement demonstrates the strong potential of remote sensing techniques for estimating peatland subsidence.

However, the results should be compared more thoroughly with estimates obtained by other methods provided at Biebrza Valley - from Eddy Covariance ex Fortuniak 2026 and chamber measurements carried out with other researchers at Biebrza Valley and the similarities and differences should be discussed to better demonstrate the reliability and limitations of the proposed approach.

In the review, I have concerns about the validation.

The problem is that the validation was based solely on measurements of the peatland surface's settlement relative to 11 piezometers driven into the mineral soil beneath the peatland. Such validation assumes that the mineral soil beneath the entire peatland remains stable throughout the entire study period, and that any deformation—whether subsidence or uplift—is entirely attributable to the degradation, shrinkage or accumulation of peat, or its swelling in the case of uplift. This need not be the case at all and has in no way been proven, as no relative measurements of vertical movements between the piezometers have been carried out.

Such validation could be carried out more precise by installing a permanent GNSS station on each piezometer, which would enable the relative vertical movements of the piezometers in relation to one another to be monitored with very good temporal resolution and the stability of the ground beneath the peatland to be assessed.

Such an analysis naturally involves the cost of setting up a GNSS station on each piezometer, and this must be done immediately before the start of the entire study. The accuracy of relative vertical displacements between permanent GNSS stations is approximately 1 cm.

A second potential solution, without installing GNSS stations, that could reduce the uncertainty of these measurements would be to extend the spatial coverage of the interferometric analysis slightly beyond the peatland area. The spatial buffer could be introduced around the peatland to compare the vertical ground movements of the surrounding mineral soils with the displacements observed within the peatland itself.

If the observed vertical displacements within the peatland are indeed caused exclusively, or primarily, by processes occurring within the peat rather than by movement of the underlying substrate, then a clear transition in vertical motion should be observable at the boundary between the peatland and the adjacent mineral terrain. This second approach would, of course, provide only an approximate and preliminary assessment of the stability of the mineral substrate.

I also have some comments about the technical approach used to validate the interferometric product with piezometer measurements, as presented in the article 1 Fig. 6. Each of the eleven plots compares a deformation trend derived from only a few interferometric observations (approximately one per year) with a deformation trend obtained from piezometer measurements based on several dozen field observations collected much more frequently. This approach has to be discussed, because piezometer measurements during periods for which there are no adequate interferometric measurements, they may significantly influence the estimated trend line. I believe that the trend for the piezometer measurements should be calculated exclusively from those observations that coincide with the dates of the available interferometric measurements. I suspect that this would lead to greater discrepancies between the two trends, but it would be methodologically correct.

A closer examination of the same figure shows that, for several piezometers—particularly: 1, 7, 9, 10, and 11—there are considerable discrepancies between the two trends. These differences may result either from movement of the mineral substrate beneath the peatland or from inaccuracies and errors in the interferometric processing itself. Without independent external validation, it is impossible to determine which of these factors—or perhaps both—is responsible for the observed discrepancies.

It is also unclear whether the authors of the interferometric analysis were able to adequately remove the influence of factors affecting the interferometric signal, such as changes in radar wave penetration depth caused by variations in soil moisture between acquisition dates, changes in vegetation cover, or ground temperature, which may also affect radar wave penetration depth. The PhD candidate minimized these effects by selecting images acquired during the same season and under conditions of minimal vegetation cover. However, at the spring time very often there is much water on a surface or great differences in moisture conditions.

There is also no analysis of how the uncertainty associated with the quality of the vertical displacement product propagates into the uncertainty of the estimated amount of carbon released from peatlands to the atmosphere. This issue is particularly important because no method has been proposed to assess the accuracy of the estimated carbon emissions.

The PhD Candidate presented the recommendations and implications for the future as:

Upscaling the approach; Machine learning integration: Advancing to Tier 2 and 3 greenhouse gas reporting

By observing the subsidence rates the PhD Candidate indicated that the Biebrza Valley is actively losing its peat resource. Without timely and effective rewetting interventions designed through modern environmental engineering, peat oxidation will continue, ultimately leading to complete peat mineralization and irreversible loss of both water retention capacity and carbon storage function.

In summary, the doctoral dissertation is of high scientific quality and innovative. The research provides an original and significant contribution to the field.

The research objectives are clearly formulated and supported by well-defined scientific hypotheses that are logically connected to the methodology and expected outcomes.

The selection of three peatland complexes representing different stages of degradation provides an appropriate experimental design and enables meaningful comparisons across contrasting environmental conditions.

The PhD candidate has demonstrated excellent research skills, critical thinking, and a thorough understanding of the subject. The applied methodology is very interesting, and new for Polish sites.

The Candidate cited a wide range of literature.

In my opinion, the dissertation fully satisfies the requirements for **the award** of the doctoral degree, and I strongly support its acceptance.

Po analizie wszystkich wymienionych w przedstawionej recenzji uwag stwierdzam, że rozprawa spełnia wymagania zawarte w Ustawie Prawo o Szkolnictwie Wyższym i Nauce z dnia 20 lipca 2018 roku o stopniach naukowych i tytule naukowym w Dzienniku Ustaw z 2024 poz. 1571. Wnioskuję, zatem o dopuszczenie mgr Pouya Ghezel Ayagh do publicznej obrony tej pracy.

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