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Katedra Geoinfomatyki, Kartografii i Teledetekcji

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Review of the doctoral dissertation of M.Sc. Sanjana Dutt

entitled:

Forest Fragmentation Dynamics in Tuchola Forest, Poland.
A Multiscale Analysis Using Remote Sensing

prepared under the supervision of: Dr. hab. Mieczysław Kunz, Prof. of NCU
at the *Faculty of Earth Sciences and Spatial Management,*
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The formal basis for this review is Resolution No. 21/2025 of the Council of the Discipline of Earth and Environmental Sciences of the Nicolaus Copernicus University in Toruń, dated 10 October 2025, concerning the appointment of reviewers in the proceedings for the awarding the degree of doctor to M.Sc. Sanjana Dutt. The legal basis is provided by the current provisions of the Law on Higher Education and Science (consolidated text: Journal of Laws of 2024, item 1571, as amended) and Resolution No. 38 of the Senate of Nicolaus Copernicus University, dated 26 September 2023, on the procedure for the conferral of the doctoral degree at Nicolaus Copernicus University in Toruń.

The doctoral dissertation is written in English and comprises 154 pages of English-language typescript basing on a cycle consisting of:

1. two published scientific articles in journals: *Ecological Indicators* (IF_{2024} = 7.4; $MNiSW_{2024}$ = 200 points) and *Bulletin of Geography. Physical Geography Series* (IF_{2024} = 0.8; $MNiSW_{2024}$ = 40 points);
2. a published book chapter in the book of Młynarczyk, A. (ed.), *Środowisko przyrodnicze jako obszar badań*, Vol. IV, Bogucki Wydawnictwo Naukowe (20 MNiSW points);
3. two manuscripts submitted to international IF journals:
   a) *Landscape Ecology* (Dutt, S., Remmel, T.K., Rivas, C.A., Mazziotta, A., & Kunz, M. (2025). *Advancing Forest Fragmentation Analysis: A Systematic Review of Evolving Spatial Metrics, Software Platforms, and Remote Sensing Innovations*),
   b) *GIScience & Remote Sensing* (Dutt, S., Wojtasik, J., Justeau-Allaire, D., & Kunz, M. (2025). *How does fragmentation reshape forests? Tracking dominant ecological processes across core, transitional, and rare zones*).

The cumulative Impact Factor according to Web of Science amounts to 8.2, the total number of MNiSW points is 260, and the work (the Ecological Indicators paper) has received seven citations in Web of Science as of 3 January 2026.

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Copies of the published scientific papers and submitted manuscripts constitute an integral part of the doctoral dissertation, which has a structure typical of doctoral theses based on a collection of scientific articles. The core of the dissertation consists of a 45-page author's summary and an appendix entitled *Appendix: Full-text of 5 Publications*, which includes copies of the scientific publications forming the collection of articles within the meaning of Article 187(3) of the Act. The doctoral dissertation contains abstracts in both Polish and English in accordance with the requirements set out in Article 187(4) of the Act.

Unfortunately, statements from the co-authors specifying the individual contributions of the doctoral Candidate and the respective co-authors were not included. However, in all publications and submitted manuscripts Ms. Sanjana Dutt is the first and corresponding author, which confirms her key role in the preparation and submission of the manuscripts.

The structure of the dissertation is typical of doctoral theses and includes the following parts:

- title page; dedication to parents; *Table of Contents*; motto; *Acknowledgments*; *Abstract*, *Keywords* (EN); *Streszczenie*, słowa kluczowe (PL); *List of Scientific Publications Related to the Thesis with Impact Factor (IF) and Polish Ministry of Science and Higher Education (MNiSW) points*; *Other Scientific Contributions with Impact Factor (IF) and Polish Ministry of Science and Higher Education (MNiSW) points*. The above elements occupy 15 pages.
- *Chapter 1: Introduction*; occupies 7 pages and provides a clear, well-structured, and scientifically sound introduction to forest fragmentation, effectively situating the dissertation within contemporary landscape ecology and remote sensing research. The doctoral Candidate demonstrates good knowledge of the literature (30 cited references in the chapter) and convincingly justifies the importance of studying fragmentation in temperate forests, which remain less explored than tropical systems. A major strength of the chapter is the coherent presentation of the research concept, linking landscape structure with Sentinel-2 vegetation indices and management-relevant outcomes. This integrative approach supports robust ecological interpretation and enhances the applicability of the results to Natura 2000 site management and spatial conservation policy. The selection of the Tuchola Forest Biosphere Reserve as a case study is well justified, given its structural homogeneity, disturbance history, and spatial configuration, which together provide a suitable natural laboratory for fragmentation research. Methodologically, the chapter is characterized by clarity and reproducibility, with well-defined parameters, analytical procedures, and validation strategies reflecting best practices in landscape ecology and remote sensing. The research questions, objectives, and hypotheses are clearly formulated, internally consistent, and well aligned with the applied methods and datasets. Overall, the chapter establishes a solid conceptual and methodological foundation for the dissertation and makes a meaningful contribution to the analysis and monitoring of fragmentation in temperate forest ecosystems. A few minor comments can be made for future research. Eight of the 30 publications published in the last four years (2022-2025) were cited. This section, along with the discussion of the results, should include more current publications showing what methods are currently being developed and what results researchers are achieving.

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There is cited Fahrig, 2019 (page 16), which is not listed in the reference list (Fahrig et al., 2019 is). The PhD student uses so-called citation trains, i.e., a cluster of several subsequent citations, e.g., 'Arroyo-Rodríguez et al., 2017; Fletcher et al., 2018; Fahrig, 2019; Ma., et al. 2023', which do not explain the contribution of individual articles to the discussed topic. It is better to cite a given article by providing specific achievements (methodology, results), confirming the presence of the discussed issues in the literature, and citing specific solutions/results.

- *Chapter 2: The Tuchola Forest Biosphere Reserve* (4 pages). This chapter provides a clear characterization of the research area, which covers one of the most important UNESCO Man & Biosphere reserves. The text effectively demonstrating its relevance as a model system for studying fragmentation processes in temperate forests. By integrating geographical, ecological, and policy contexts, the chapter convincingly situates TFBR within both regional conservation practice and global frameworks such as the Kunming–Montreal Global Biodiversity Framework and REDD+ MRV. A key strength of the chapter is the thorough description of TFBR's spatial structure, UNESCO zoning, and postglacial landscape, which together support multi-scale analyses of fragmentation and disturbance. The inclusion of field-based photos evidence further strengthens the empirical grounding of the analysis. The chapter effectively links observed fragmentation patterns to conservation challenges, including biodiversity loss, management constraints within Natura 2000, and pressures from forestry and agriculture. Importantly, it demonstrates how the analytical tools developed in the thesis—such as fragmentation susceptibility mapping and remote-sensing-based vegetation monitoring—can directly inform policy-relevant conservation actions.
- *Chapter 3: Materials, Methods, and Analytical Framework* (6 pages) presents a comprehensive, transparent, and methodologically proper framework for quantifying forest fragmentation. A key strength of the chapter is the development of a scalable and fully reproducible analytical workflow that explicitly links landscape structure (FAD, MSPA, classical metrics) with remote sensing data (Sentinel-2 vegetation indices) and management-oriented outputs (susceptibility mapping and zone-specific guidance). The clear declaration of all scale- and comparability-related parameters reflects best practices in policy-relevant landscape and remote sensing research. The chapter demonstrates proper use of different tools, multi-sensor datasets, and open-source platforms to assess fragmentation processes. The integration of CORINE, Landsat-8, PALSAR, and Sentinel-2 data enables robust multitemporal, -scale assessment (harmonization of spatial resolution and analytical windows enhances cross-sensor comparability) based on could computing solution (Google Earth Engine and open source packages), which strengthens transparency and reproducibility of the outcomes. The statistical and machine-learning methods were well chosen and clearly motivated, balancing predictive performance with interpretability through spatial cross-validation, ensemble modelling, and Bayesian Weight-of-Evidence approaches.
  The doctoral dissertation lacked concise information, such as a table of input data used (a list of satellite scenes, their acquisition dates, vector data with information about individual units and their current validity). References to the authors of used remote sensing indices and their full names were also missing, and details of the methods for

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verifying the obtained data and the developed models should have been highlighted to clearly assess how the achievements were verified.

- *Chapter 4: Synthesis, Contributions, and Future Directions* (6 pages). The text provides a well-structured, yet significantly under-concise, synthesis of the doctoral research included in this dissertation. This text provides a coherent narrative that addresses the research questions. The chapter successfully integrates multi-scale remote sensing data, landscape metrics, and advanced analytical methods to demonstrate how forest fragmentation processes operate at various spatial scales in the Tuchola Forest Biosphere Reserve. A key strength of the chapter is the clear link between structural patterns of fragmentation and functional ecological responses recorded by remote sensing sensors. The findings indicate that fragmentation effects are scale-dependent and disproportionately impact individual zones of the Park. The chapter clearly outlines the key scientific and practical contributions of the dissertation, including the development of an open and replicable analytical framework, mapping of vulnerability to fragmentation, and zone-specific conservation strategies. A clear link to international policy frameworks (Kunming–Montreal Global Biodiversity Framework, REDD+ MRV, and the Sustainable Development Goals) enhances the work's relevance beyond the research area. Limitations are discussed critically but should be based on a larger number of reference publications (these are presented in individual publications, but in the thesis they should be presented as a separate chapter: Discussion of the obtained results to highlight innovative methodological achievements and outcomes in the context of the current literature). The doctoral Candidate proposed directions for future research; these are justified and logical.
  To sum up, this chapter is interesting, but significantly too short, it is a key part of the doctoral dissertation and should be significantly expanded with specific results and observations, which could possibly be included in a chapter: Discussion of the outcomes.
- *Chapter 5: Conclusions* (2.5 pages) contains a well-structured conclusion, but it is a mixture of Summary and Conclusions, as the Summary should precisely address the assumptions of the work, including the objectives and hypotheses. The Conclusions, on the other hand, should present key, synthetic conclusions drawn from the work. This chapter demonstrates scientific maturity, precisely addressing each research question and consistently linking landscape structure, ecological processes, and feasible conservation strategies within a unified "pattern-process-action" model. However, the text presented is too general.
  The strength of the chapter is its convincing demonstration that forest fragmentation in the Tuchola Forest Biosphere Reserve is not merely a spatial pattern but a driver of measurable functional stress, particularly in transitional and sparse zones dominated by marginal zones. Furthermore, the substantive and methodological contributions are clearly, if too broadly, emphasized through original, well-grounded research topics, a well-chosen set of research tools, the development of an open, repeatable workflow, and the implementation of methodological assumptions, which allowed for the generation of relevant and valuable results. The management and policy implications

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are practical, well-grounded in results, and clearly aligned with international frameworks such as the Kunming–Montreal Global Biodiversity Framework.

- *References.* The list of cited publications in the doctoral dissertation (excluding those cited in individual articles that are components of this dissertation) totals 53 items. Twenty-eight items are publications published before 2020 or currently in print, and 25 items are recent articles published between 2020 and 2025. It should be noted that the author did not provide DOI numbers for some of the articles, which is currently standard practice. Furthermore, citation standards vary; for example, article names are written with their full names, and in some cases, abbreviations are used: sometimes, 'et al.' is used after citing two authors: (Britton, J., Abatzoglou, J.T., et al., (2024).), and sometimes all authors are listed or multiple names are followed by '....' (Brown, C.F., Brumby, S.P., Guzder-Williams, B., Birch, T., Hyde, S.B., Mazzariello, J., ... & Tait, A. M. (2022).). In the case of monographs/books/chapters in books, the publisher and place of publication should be provided ('CRC Press.' or 'Springer'). The dot at the end of the citation is missing in case of www addresses.
- *Appendix. Full-text of 5 Publications*:
    - **Dutt, S.,** Remmel, T.K., Rivas, C.A., Mazziotta, A., & Kunz, M. (2025). Advancing Forest Fragmentation Analysis: A Systematic Review of Evolving Spatial Metrics, Software Platforms, and Remote Sensing Innovations. *Landscape Ecology* (Under review, journal metrics: IF 5.1; 140 MNiSW points.
    - **Dutt, S**., & Kunz, M. (2022). Land use/cover changes using Corine Land Cover data following hurricanes in the last 10 years: A case study on Tuchola Forest Biosphere Reserve. In: Młynarczyk, A. (ed.): *Środowisko przyrodnicze jako obszar badań*. Vol. IV. Bogucki Wydawnictwo Naukowe, Poznań: 25–42 (Book Chapter). 20 MNiSW points.
    - **Dutt, S.,** & Kunz, M. (2024). Landscape metrics of the Brusy Commune before and after wind-storm: An assessment based on Landsat-8 data. *Bulletin of Geography. Physical Geography Series* 26: 19–33. IF 0.8, 40 MNiSW points. 0 citations (Scopus, 07/01/20226).
    - **Dutt, S.,** Batar, A.K., Sulik, S., & Kunz, M. (2024). Forest ecosystem on the edge: Mapping forest fragmentation susceptibility in Tuchola Forest, Poland. *Ecological Indicators* 161: 111980. IF 7.4, 200 MNiSW points. 7 citations (Scopus, 07/01/20226).
    - **Dutt, S.,** Wojtasik, J., Justeau-Allaire, D., & Kunz, M. (2025). How does fragmentation reshape forests? Tracking dominant ecological processes across core, transitional, and rare zones. *GIScience & Remote Sensing* (Under review, journal metrics: IF 6.9, 100 MNiSW points).

Evaluation of the Dissertation Articles/Manuscripts

Dutt, S., Remmel, T.K., Rivas, C.A., Mazziotta, A., & Kunz, M. (2025). Advancing Forest Fragmentation Analysis: A Systematic Review of Evolving Spatial Metrics, Software Platforms, and Remote Sensing Innovations. *Landscape Ecology* (Under review).

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This is an important and valuable manuscript that should have been prepared first, as it demonstrates the potential of remote sensing and machine learning in forest ecology. It provides a research framework that forms the basis of the doctoral dissertation. A drawback is that it was submitted for publication in 2025, effectively the final period of preparation for the doctoral dissertation. This manuscript presents a comprehensive synthesis of a review of 138 peer-reviewed studies published between 1990 and 2025, assessing the state of knowledge in the field of forest fragmentation analysis. It is a systematic literature review of the rapidly evolving interdisciplinary field of forest ecology, remote sensing, and machine learning. The work is ambitious in scope, technically robust, and well-prepared to serve as a reference for researchers and practitioners working at the intersection of landscape ecology, forestry, and remote sensing. A key strength of the manuscript lies in its conceptual approach: analyzing forest fragmentation in a connected sequence—data sources, change detection methods, and landscape pattern indicators. This perspective helps readers understand how individual methodological solutions allow for the assessment of changes occurring in forest ecosystems, taking into account the scale of the phenomenon, available data and algorithms, and the assessment of ecological phenomena. Another advantage is the identification of limitations, such as data inconsistencies, different scales of analysis, edge definitions, composition strategies, and change detection parameters. The manuscript highlights how geoinformatics platforms, open-source scripting environments, and cloud systems now function together as integrated analytical pipelines. This realistic approach reinforces the paper's relevance for monitoring large areas over various time horizons and comparing the obtained results, including detecting the dynamics of changes.

The manuscript should clearly present its contribution to the literature, as many comparable publications can be found in the literature. A broader and more up-to-date literature review, including technological innovations, is certainly a distinguishing feature. Furthermore, the interpretation of the results' applications, particularly in terms of ecological analyses, is somewhat unevenly presented, for example, the connections between structural fragmentation metrics and biological ecosystem responses, as the authors did not delve deeply into the theory of forest ecology to explain the gaps between remote sensing observations and the environment. I fully understand that this is a difficult and complex process, as the spectral response is a result of many processes that are extended over time, resulting in delayed ecological implications.

Dutt, S., & Kunz, M. (2022). Land use/cover changes using Corine Land Cover data following hurricanes in the last 10 years: A case study on Tuchola Forest Biosphere Reserve. In: Młynarczyk, A. (ed.): *Środowisko przyrodnicze jako obszar badań*. Vol. IV. Bogucki Wydawnictwo Naukowe, Poznań: 25–42 (Book Chapter). 20 MNiSW points.

This article addresses an important and timely topic: the impact of extreme windstorms on forest ecosystems, and the study area was the Tuchola Forest Biosphere Reserve (TFBR). The analysis required the integration of Corine Land Cover (CLC) data with landscape metrics based on a relatively long period of observation of ongoing changes (1990–2018, during which three extreme windstorms occurred in 2012, 2017, and 2021). The article under review builds on valuable foundations in the integration of satellite data and their products, combined with methodologies developed in landscape ecology to assess changes observed in land cover, fragmentation, heterogeneity, and resilience. The potential of landscape indicators reflecting

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windbreaks, emergency logging, and path regeneration, which alter the spatial functions of individual forest fragments, is well-developed. The use of Corine LC data impacted the scale of the analysis, as the minimum mapping unit is 25 ha, which limits the ability to detect minor disturbances typical of hurricane damage and thus limits the scale of the analysis. It would be worthwhile to utilize original Landsat TM-OLI images (1984-2024) and perform analyses with a pixel resolution of 30 m, thus improving the analysis of individual patches affected by windfalls. Furthermore, the six-year acquisition intervals for Corine maps make it difficult to assess the impacts and recovery from individual windfalls, particularly the effects of the 2021 event, which was not fully accounted for. This paper would have benefited from the use of more extensive statistical methods to assess the significance of the observed changes.

Nevertheless, despite these limitations, the methods used are valuable and appropriate for achieving the stated objectives, as they cover a significant area and require a significant analysis time. The results clearly indicate significant forest loss, a sharp increase in transitional forest/shrub area, and increasing landscape fragmentation, consistent with large-scale wind disturbance followed by regeneration. The observed increase in the Shannon Diversity Index is correctly interpreted as an increase in landscape heterogeneity, not ecological improvement.

The discussion effectively synthesizes landscape indicators with land cover changes and introduces the Landscape Change Index (LCI) as an integrating measure. The identification of transitional forest/shrub expansion as a key signal following disturbance is particularly strong.

In summary, this paper provides valuable empirical evidence on the long-term dynamics of forest landscapes under recurring extreme weather events in Central Europe. It demonstrates the usefulness—and limitations—of CLC data in disturbance analysis and provides insights relevant to forest management, conservation planning, and climate change adaptation strategies. The study also highlights the need to utilize higher-resolution datasets (Sentinel, LiDAR) and better temporal coverage, which positions the work well for future research. Overall, this is a methodologically sound and scientifically significant study that makes a significant regional contribution to landscape ecology and disturbance research. Its strengths lie in its long-term perspective, the integration of landscape metrics, and its focus on a protected biosphere reserve. The main weaknesses concern data resolution, causal inference, and limited statistical testing.

Dutt, S., & Kunz, M. (2024). Landscape metrics of the Brusy Commune before and after wind-storm: An assessment based on Landsat-8 data. *Bulletin of Geography. Physical Geography Series* 26: 19–33. IF 0.8, 40 MNiSW points.

This article addresses an important and contemporary research problem: forest landscape fragmentation following extreme windstorms (derechos), analyzed using multi-temporal Landsat-8 data and landscape metrics. The focus on the Brusy commune in the Tuchola Forest Biosphere Reserve is of significant regional importance, particularly given the scale of destruction caused by the 2017 storm. This study contributes to a growing body of literature integrating remote sensing, GIS, landscape ecology, and machine learning, which is crucial for contemporary forest monitoring and management. A key contribution of the article is the shift from single-date image analysis to multi-date seasonal composites obtained from Google Earth Engine (GEE). One of the study's main advantages is the robust data processing. Using 23

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Landsat-8 images to generate median composites from the summer before and after the derecho significantly increases the classification stability and temporal representativeness. The use of Random Forest (RF) classification is justified and consistent with best practices in land cover mapping, and the reported overall accuracy of 0.92 indicates high classification performance. The study is also methodologically sound in its use of landscape metrics, selected based on established literature. Metrics such as number of patches (NP), mean patch size (MPS), edge density (ED), total edge (TE), and the Shannon Diversity Index (SHDI) are suitable for detecting fragmentation and heterogeneity at both the class and landscape levels. Analysis at two scales (class and landscape) strengthens the ecological interpretation of the results.

The results clearly indicate increased fragmentation after the 2017 derecho, particularly in the forest and pasture classes. The steady increase in NP and ED along with the decrease in MPS provides a consistent and convincing picture of fragmentation. The authors correctly interpret the stability of the SHDI as an indication that short-term structural disturbances do not necessarily translate into immediate changes in compositional diversity. The article is well-grounded in landscape ecology theory, particularly with respect to fragmentation and scale dependence. However, the discussion could be strengthened by a deeper understanding of ecosystem resilience and regeneration theory, particularly with respect to distinguishing ecological degradation from structural reorganization following disturbance, for example, in forested areas, commercially used forests, or privately owned forests.

Overall, the article represents a solid and methodologically sound contribution to the field of forest disturbance and landscape ecology. Its strengths lie in the innovative use of multi-temporal Landsat imagery, the integration of machine learning with landscape metrics, and the clear demonstration of storm-induced fragmentation patterns.

Dutt, S., Batar, A.K., Sulik, S., & Kunz, M. (2024). Forest ecosystem on the edge: Mapping forest fragmentation susceptibility in Tuchola Forest, Poland. *Ecological Indicators* 161: 111980. IF 7.4, 200 MNiSW points.

This article addresses a crucial and timely research problem: forest fragmentation under the combined influence of extreme winds and anthropogenic land-use changes. This is a crucial element of ecosystem functioning; the importance of this problem was recognized many years ago with the creation of Natura 2000 sites, which were intended to provide corridors and habitats for living organisms. This is particularly important because, in Europe and many other continents, forest fragmentation occurs, for example, for the construction of communication infrastructure or settlements in attractive natural locations, which limits animal habitats and introduces new species, their odors, and diseases. The authors focused on a valuable area (buffer zones and commercial forests should also be included) to assess the changes that have occurred in the context of accelerating climate change and increasing disturbance regimes in European forests. The study aligns with current priorities in landscape ecology, forest conservation, and climate change adaptation research. The originality of this paper lies primarily in its integrated approach, combining multi-source remote sensing data, ecological indicators, and Bayesian modelling to map forest vulnerability to fragmentation. Although each of these methods has been used individually in previous studies, their combined application to the analysis of forest vulnerability to fragmentation after disturbance, particularly in the Polish context, represents

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a novel and significant contribution. The explicit focus on vulnerability mapping rather than solely on retrospective fragmentation assessment distinguishes this study from most of the existing literature in Poland.

This paper demonstrates a strong conceptual foundation in landscape ecology, fragmentation theory, and disturbance ecology. Key concepts such as edge effects, scale dependence, forest connectivity, and ecosystem resilience are clearly articulated and well supported by a substantial and relevant literature. The conceptualization of fragmentation as a process driven by both natural disturbances (derechoes) and human pressures (arable land expansion, proximity to infrastructure) is theoretically sound and consistent with contemporary ecological thinking. The study effectively positions the 2017 windstorm as a critical disturbance event, justifying the chosen time frame (2015–2020). However, although the conceptual discussion of fragmentation impacts is comprehensive, the distinction between direct disturbance effects and post-disruption management responses (e.g., salvage logging, land conversion after windfall) could be more precisely formulated. This would further strengthen the causal interpretation.

The multicollinearity analysis and subsequent reduction of predictor variables reflect good statistical practice and demonstrate methodological maturity. The final selection of eight independent variables balances ecological significance with statistical rigor. The weight-of-evidence (WoE) modelling framework was appropriately selected for vulnerability mapping and described clearly. The mathematical formulation, variable weighting, and construction of the Forest Fragmentation Vulnerability Index (FFSI) are clearly presented and reproducible.

Despite its strengths, the article has several limitations. For example, the spatial and temporal patterns strongly suggest fragmentation caused by the storm, and causality remains largely inferred rather than directly verified (e.g., water shortage causing evapotranspiration stress and weakened root systems in some areas). The role of post-storm forest management (e.g., emergency logging, reforestation strategies) is not quantitatively separated from the effects of natural disturbances. In summary, the article represents a coherent, original, and influential contribution to research on landscape ecology and forest disturbances. Furthermore, it promotes Polish research units and Polish research areas that are on the UNESCO international list.

Dutt, S., Wojtasik, J., Justeau-Allaire, D., & Kunz, M. (2025). How does fragmentation reshape forests? Tracking dominant ecological processes across core, transitional, and rare zones. *GIScience & Remote Sensing* (Under review, journal metrics: IF 6.9, 100 MNiSW points).

This paper presents a methodologically compelling and conceptually well-structured assessment of the impact of forest fragmentation on key ecological processes in clearly defined spatially defined fragmentation zones. By integrating foreground density-based zonation (FAD), multi-temporal Sentinel-2 vegetation indices, and field-based ecological attributes from the Polish Forest Data Bank, this study advances fragmentation research from descriptive pattern analysis toward process-oriented diagnostics. A key strength of the paper is the explicit stratification of the fragmentation context into core, transition, and sparse zones. This approach effectively separates forest interior dynamics from edge-dominated processes and demonstrates that fragmentation effects are strongly zone-dependent. The use of interpretable ensemble models (Extra Trees, LightGBM) combined with permutation importance and partial

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dependence plots provides a distinct methodological advantage, enabling ecological interpretation rather than purely predictive modelling. The results convincingly show that sparse zones experience early degradation, moisture stress, and structural simplification, while core areas maintain ecological stability, confirming theoretical expectations regarding landscape ecology.

The study's reliance on Sentinel-2 data and iterative workflows enhances its scientific and practical value, enabling the framework to be transferred to other temperate forest systems. Identifying pigment and moisture sensitivity indicators (e.g., NDRE, GARI, NDMI) as early warning indicators is particularly important for operational forest monitoring and adaptive management. This paper makes a significant scientific contribution to research on forest fragmentation, in this case protected areas. However, it would be worthwhile to also consider commercially used forest areas where logging and plantings generate new phenomena for forest inhabitants by altering animal migration routes.

Substantive evaluation of the doctoral dissertation

The PhD Candidate undertook the ambitious task of combining geospatial data processing procedures derived from satellite data recording reflected electromagnetic radiation from various objects, representing the spectral characteristics of complex environmental processes occurring in different time and space with varying frequency and intensity, with processes occurring in nature that cannot be directly captured by remote sensing, and with real environmental and ecological phenomena measured using different scientific methodologies. This required extensive knowledge of both natural sciences and algorithms, geoscience, and computer science. The results obtained are valuable because they combine quantitative and qualitative descriptions, and some of the data comes from different researchers, thus being subjective and characterized by varying degrees of accuracy. The research goals were achieved because the author, drawing on an extensive and up-to-date literature review, implemented the latest remote sensing data and machine learning algorithms to generate maps presenting components of the natural environment, analysing forest fragmentation, which has a profound impact on biodiversity, carbon sequestration, and ecosystem resilience to ongoing changes.

This dissertation focuses on the dynamics of fragmentation in the Tuchola Forest Biosphere Reserve (TFBR; Polish: RBBT), a landscape shaped by long-term monocultural forest management, strong land use pressures, and extreme disturbances, particularly derechos, which occurred several times during the period covered by the analysis. The study area is among the most valuable in Poland and worldwide, as it is under the patronage of UNESCO Man & Biosphere. Therefore, the observations are valuable to the international community. However, the analysis still needed to include areas commercially used by the State Forests, as they are subject to regular logging and replanting, which significantly alter local environmental conditions. The second element that would require modification is the use of Corine data. These valuable data are problematic, but the minimum mapping area of 25 hectares leads to a number of generalizations. Furthermore, the latest edition of the Corine map is still in preparation, so current data could not be included. Land cover classifications for individual periods could easily be performed independently (Landsat TM data have been available since 1983), so the generated maps would be of comparable quality for the entire study area.

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Nevertheless, Ms. Sanjana Dutt used highly valuable, multi-source and multi-temporal satellite data with varying spatial resolutions (Sentinel-2, ALOS PALSAR, Landsat-8, CORINE). All this data was properly acquired, processed, and applied. This is highly valuable, as it required knowledge of a range of procedures and application skills, including the use of proprietary programming scripts and advanced Google Earth Engine. The results of this work were combined with advanced landscape measurements and ecological measures, which, combined with machine learning methods, allowed for a comprehensive understanding of the reality of land fragmentation as a multi-scale and multi-temporal process of structural and functional fragmentation of forest space, the identification of dominant ecological processes, and the development of monitoring strategies that support protection and increased forest resilience.

The dissertation focused on four main and ambitious research questions:

- How have methods for assessing forest fragmentation evolved over time?
- How do fragmentation and multi-scale disturbances alter forest structure and landscape integrity?
- Which ecological processes dominate fragmentation zones (core, transitional, sparse)?
- Which vegetation indicators are most effective for monitoring, prioritizing, and planning conservation?

The questions posed demonstrate significant research maturity and excellent scientific expertise (based on both extensive theoretical knowledge and mastery of sound research techniques—the ability to acquire, process, and analyse diverse data) and the ability to analyse the obtained results to develop interdisciplinary insights. The result is five peer-reviewed articles/manuscripts that:

- document the interdisciplinary integration of metrics obtained from various sources for assessing patches and their integration to assess landscape coherence (Article 1);
- identify baselines prior to landscape disturbance and fragmentation assessment (Article 2);
- estimate the loss of dense (core) forest areas and the expansion of edge zones in the landscape following the 2017 storm (Article 3);
- identify areas at high risk for hurricane-force winds due to proximity to agricultural land and vulnerable terrain using a proprietary landscape assessment framework using the Fragmentation Susceptibility Modelling Framework (Article 4);
- identifies water stress and other selected parameters as a result of dominant ecological processes analysed using remotely sensed indicators based on Sentinel-2 imagery and machine learning methods (Article 5).

Publication No. 1 should be prepared first, because the Candidate has obtained a valuable foundation for subsequent work in the form of knowledge of what and how is done in the field of research. Each publication is a conceptually valuable work, clearly demonstrating a continuation of the research initiated in the previous publication. However, the unresolved question remains whether using Landsat data to create more detailed information about the area since the 1980s would have provided more detailed information about the changes occurring before the windfall. For example, was the damaged forest in any way in worse condition than

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the surrounding areas? Was the vertical structure of the forest disturbed? Would lower forest levels allow for faster regeneration of the windfalls?

The proposed methodology can be transferred beyond the TFBR area to temperate and boreal forests, particularly through cloud platforms such as Google Earth Engine. The research directly supports international policy frameworks, including the Kunming–Montreal Global Biodiversity Framework (30x30 by 2030) and the REDD+ Monitoring, Reporting, and Verification (MRV) framework, while contributing to Sustainable Development Goals 15 (Life on Land), 13 (Climate Action), and 6 (Clean Water and Sanitation) by providing practical tools for biodiversity conservation and climate change adaptation in temperate forest landscapes.

I strongly recommend this doctoral dissertation because the Candidate focused on a challenging and spatially and temporally variable research subject, drawing on a well-established methodological assessment of the occurring phenomena, utilizing widely recognized and effective research algorithms that yielded valuable results. The results of Sanjana Dutt's research have not yet been exhausted, as access to new, high-resolution data allows for the modification, improvement, and adaptation of individual models to specific socio-economic challenges, for example, during a changing climate, modelling water shortages/floods, and reduced river water flows in other areas, such as commercial forests or private woodlots and shrublands. The doctoral dissertation is based on a large amount of current data, which was duly acquired, verified, and processed by a series of optimized algorithms, offering valuable quantitative and qualitative results that confirmed the validity of the adopted research methodology. The doctoral thesis is very well grounded in the literature on the subject. The Candidate cites numerous current literature sources and confidently demonstrates her excellent research skills. She is not only able to propose an interesting research procedure but also to implement it effectively, placing the obtained results within the relevant literature. Ms. Sanjana Dutt developed and successfully tested the integration of various data processing models, and published the obtained results in prestigious international journals covering the specific modules of the thesis. This is valuable because the professional editorial teams and reviewers enabled the research concepts to be refined to international standards, ensuring high-quality publications. This will generate interest among readers both in the natural environment and data processing (algorithms, computer science), strongly promoting Poland and Polish research institutions, as well as research areas protected by UNESCO.

A strength of this doctoral dissertation is its integration of the latest methods developed by ecologists, geoinformaticians, remote sensing specialists, and programmers. This allows for the integration of the most important challenges of individual disciplines in an interdisciplinary approach. This makes this dissertation fit into the canon of currently developing scientific topics. Although it consists of a series of articles published in journals with diverse subject areas, it clearly outlines the continuity of the methodological concept and also provides current technological solutions for ecologists, planners, park protection services, and naturalists. Machine learning methods, satellite imagery, and 3D data demonstrate their enormous potential not only in land cover mapping but also in forestry, allowing for greater automation of verification procedures and the refinement of existing maps. Conducting geoinformatic analyses, the Candidate had access to large data sets, allowing for the retention of sufficiently large samples of processed data. Furthermore, the implementation of various models required

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appropriate data processing procedures to systematize and objectify the analysis of individual stages and verify the obtained results. The resulting maps are valuable for monitoring the environment and socio-economic development of Poland. This is an important aspect of the work, as the developed monitoring tools allow for the analysis of ongoing changes in a repeatable and comparable manner across different areas. These elements are well documented in literature sources cited not only in the dissertation but also in the publications constituting the core of the analysed doctoral dissertation.

The Candidate demonstrated excellent knowledge of: a) the theoretical background of the prepared dissertation, citing several hundred references in publications and the dissertation; b) modern geoinformatics and ecological methods; and c) alternative technological solutions using various software packages. These are valuable methodological elements, and the obtained results confirmed the validity of the proposed solutions. A strength of the study is the fusion of raster and vector data quantifying the natural environment.

From the reviewer's perspective, assessing Sanjana Dutt's contribution to the co-authored publications is somewhat challenging, especially since statements from individual co-authors were not provided. However, it is noteworthy that the Candidate is the first author of all publications, and her supervisor is a co-author on each publication, confirming that the tradition of developing young researchers under the supervision of an experienced scientist has been maintained.

The dissertation is easy to read, understandable, and substantively interesting. Individual stylistic, linguistic, or editing errors do not detract from the quality of the work. The Candidate should not use so-called citation trains, e.g. Kunz 2006; Kjelland et al. 2007; Gardner et al. 2008; Wang, Xu 2009; Kelly et al. 2011; Reif, Swannack 2014, because the contribution of the cited articles in the paper/dissertation is not clear, and the contribution of all articles should be indicated, e.g. innovative methods, interesting research concepts, interesting results that confirm/refute the adopted assumptions.

Comments on the doctoral dissertation:

- The dissertation does not include explicit author declarations specifying the individual contributions of Ms. Sanjana Dutt, M.Sc, and her co-authors. However, the individual publications contain brief statements describing the respective involvement of each author.
- The use of a large number of specialized acronyms is difficult for readers who are not experts in a given discipline; this does not detract from the substantive value, but it does hinder readability and would require careful editing.
- A more extensive discussion of the results of the doctoral dissertation is missing; this is included in every published article, but they are focused on specific topics. A more comprehensive discussion of the results would allow for a comprehensive understanding of the individual modules and demonstrate how the results compare to work conducted in other areas, such as European forests. The doctoral Candidate should definitely more thoroughly relate her own research results to the achievements of other authors to demonstrate the innovative nature of the methods used and the results obtained. There is a lack of a detailed summary in which Ms. Sanjana Dutt would precisely address the assumptions of the dissertation. This means that the research problems, objectives, and hypotheses (what was

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planned, what was implemented, and how) should be precisely presented. Key elements of the method should also be highlighted, such as which data and algorithms are crucial and which can be omitted. For example, are ALS data crucial, for example, for assessing windfall regeneration, or are SRTM data sufficient for habitat modelling?

- The reference list should include DOI numbers, although some publications do not have them, as should the publication locations of scientific monographs.
- A test/case study evaluation of the impact of low-resolution Corine data, compared to the author's land cover classification, would products based on the 30-meter Landsat pixel offer better product quality before the hurricane event, as well as regeneration of areas after windfalls?

During the public defence, the candidate should present her opinion on the impact of the analysed parameters on the condition of commercial and private forests. I am interested in whether commercial forests, where tree felling, planting, and maintenance activities are regularly carried out to optimize biomass growth, have similar ecological parameters to protected forests in the form of national parks. How do these characteristics compare to private forests, where regular maintenance is not conducted, and how the distribution of individual species is often the result of natural secondary succession?

Conclusion and justification concerning the fulfilment of the statutory requirements by the reviewed doctoral dissertation

I unequivocally recommend the doctoral dissertation by Ms. Sanjana Dutt, M.Sc., entitled *Forest Fragmentation Dynamics in Tuchola Forest, Poland: A Multiscale Analysis Using Remote Sensing*, prepared under the supervision of Dr. hab. Mieczysław Kunz, Professor at Nicolaus Copernicus University.

The doctoral Candidate has conducted a methodologically rigorous study that integrates multi-source remote sensing data with advanced machine learning techniques to optimize model architecture and parameterization. This approach demonstrates a high level of technical competence and methodological awareness, with analytical tools consistently applied in service of clearly defined environmental research objectives. The proposed methodology relies on large and diverse datasets, enabling robust and reliable results that address challenges of methodological, scientific, and societal relevance. In particular, the dissertation develops and validates an integrated analytical framework for assessing forest fragmentation dynamics across multiple spatial and temporal scales.

From a scientific perspective, the investigation of forest disturbance impacts on ecological integrity and landscape connectivity is of fundamental importance for sustainable societal development. These issues arise from competing land-use pressures, including infrastructure expansion, agricultural production, recreation, and public health, all of which must be balanced with biodiversity conservation and ecosystem sustainability. The dissertation effectively addresses key challenges in contemporary environmental research, such as the integration of heterogeneous remote sensing data sources, the linkage between structural fragmentation and dominant ecological processes, and the identification of reliable indicators for monitoring forest vulnerability and resilience using verifiable and repeatable satellite observations.

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The application of machine learning techniques enables the scalable and repeatable processing of large datasets across diverse geographical contexts. Despite limitations related to reference data availability and computational demands, the study successfully establishes a transferable and universal analytical framework with clear implications for forest conservation, sustainable management, international biodiversity and climate policy, and the development of an information-based society.

The dissertation is firmly grounded in the theoretical foundations of ecology, forestry, geography, and remote sensing, as well as in the automated processing of large datasets. The accompanying publications confirm the doctoral candidate's extensive theoretical knowledge in Earth and environmental sciences, reflected in the careful selection and critical use of relevant scientific literature. This strong theoretical background enabled the proper design and execution of the research process, including the collection and comprehensive analysis of extensive empirical material from a valuable natural area. The research objectives were fully achieved, and the results raise no methodological or substantive objections. The publication of the findings in international peer-reviewed journals with high bibliometric indicators further attests to the scientific quality of the work and enhances the academic standing of the doctoral candidate, the supervisor, and the home institution.

The results of the dissertation have clear practical applications in environmental research and management, including the support of conservation strategies for protected areas and national parks. They also contribute to broader socio-economic development through advancements in machine learning applications for environmental monitoring, spatial planning, and the optimization of land-use management under changing environmental conditions.

In conclusion, I affirm that the doctoral dissertation by Ms. Sanjana Dutt, M.Sc., demonstrates extensive theoretical knowledge in Earth and environmental sciences and confirms the candidate's ability to conduct independent, original, and well-planned scientific research. The work constitutes an original solution to a significant scientific problem and meets the criteria for doctoral research in the discipline of Earth and environmental sciences. Accordingly, I confirm that all requirements set forth in Article 187 of the Act of 20 July 2018 – *Law on Higher Education and Science* (Journal of Laws of 2024, item 1571, as amended), as well as Resolution No. 38 of the Senate of Nicolaus Copernicus University of 26 September 2023, have been fully satisfied.

I therefore fully support the continuation of the doctoral proceedings and recommend that the dissertation be admitted to public defence, leading to the awarding of the doctoral degree in the field of exact and natural sciences, discipline: Earth and environmental sciences.

Yours sincerely,

Podpisany elektronicznie przez
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