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Review of the doctoral dissertation by Ms. Sanjana Dutt, M.A., entitled:

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

Formal analysis of the dissertation

The formal basis for the review of the dissertation by Ms. Sanjana Dutt, which I hereby submit, was a letter from Prof. Piotr Hulisz, Chairman of the Council of Earth and Environmental Sciences at Nicolaus Copernicus University in Toruń, dated October 23, 2025, informing me of my appointment on October 10, 2025, as a reviewer in accordance with Resolution No. 21/2025 of the Council of Earth and Environmental Sciences.

Pursuant to the Act of July 20, 2018, Law on Higher Education and Science (consolidated text: Journal of Laws of 2024, item 1571, as amended; Article 187; point 3) - a doctoral dissertation may consist of a collection of published and thematically related scientific articles forming a coherent whole.

Structure and content of the doctoral dissertation

The doctoral dissertation submitted for review by Ms. Sanjana Dutt, is a thematically coherent collection of five related publications in English (Table 1) on the phenomenon of fragmentation of wide forest complexes. One publication (paper no. 4) has been published to date in a highly rated journal (IF= 7.4; 200 points MNiSW) and in a monograph (paper no. 2) and in the Bulletin of Geography (paper no. 3). The next two papers have been submitted to indexed Journals: Landscape Ecology and GIScience & Remote Sensing. The doctoral student was the first (lead) author of all five articles indicated in the series.

The works forming the basis of the dissertation have been published in journals specializing in landscape ecology, environmental ecology, and remote sensing. At the time of submission for review, the works submitted for the series had not yet achieved a high level of citations, with the exception of article No. 4, which is already showing a dynamic increase in citations (7 according to the Scopus database). It is entirely understandable that an increase in citations simply requires time.

Table1 . List of publications constituting the series with IF values and MNiSW scores

Article No.	Article	Journal / Publisher	IF	MNiSW points
1	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)	5.1	140
2	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.	Book Chapter, [In:] Młynarczyk, A. (Ed.): The Natural Environment as a Field of Research. Vol. IV. Bogucki Scientific Publishing House, Poznań: 25–42.	N.A.	20
3	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.	0.80	40
4	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.	7.4	200
5	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)	6.9	100

Undoubtedly, the reviewer had some objective difficulties in recognizing works 1 and 5 as full-fledged components of the series, due to unfamiliarity with the regulations at Nicolaus Copernicus University in Toruń governing the admission of publications as components of dissertations at the review stage. Unfortunately, the candidate did not attach correspondence from the editors of the journals (papers No. 1 & 5), which would have been very helpful in determining whether the works would be published or whether they had even passed the first stage of review. The PhD candidate declaration that the works have been submitted to publishing systems (no dates of emails or submissions, except for the single date of 24.09.2.25 on the qualified signature) seems to be decisive, because undoubtedly a mention such as "*accepted for publication*" from the publisher would be of great help to the reviewer. In any case, the reviewer believes that by submitting the work for review, RDNoZiŚ UMK in Toruń verified the relevant regulations, hence the reviewer will refer to the evaluation of the dissertation as a guide, published articles constituting a series, and two items submitted to publishers to supplement the series.

An additional problem for the reviewer is the statements of the co-authors (which is basically the norm) of the publications, or rather the complete lack of such attachments in the dissertation. Only in the publications can information be found about the scope of the authors' work (*CRediT authorship contribution statement)*, but since certain areas overlap, it is difficult to assess the percentage contribution. It is obvious to the reviewer that the effort of preparing the manuscript probably rested mainly with the PhD candidate, but it would be much simpler and clearer for the purposes of the review to provide the percentage shares of the co-authors as signed attachments. Despite the shortcomings, the reviewer has complete confidence in the doctoral student's declarations and her ethical attitude. I refer to this because these situations are not common for reviewers, and perhaps the committee appointed to conduct the proceedings should attach its position or the regulations of the Nicolaus Copernicus University in this matter (statements or publications in reviews).

Layout and content of the doctoral dissertation

The layout of the submitted dissertation in the form of an abstract (the so-called Guide or Summary), 45 pages in total, including the title page) begins with Acknowledgements, Abstract, Summary (in Polish), List of publications submitted to a coherent series, List of other publications. This is followed by four parts (I-IV), i.e.:

- **Part I**: Conceptual Framework consisting of the following subchapters: Background and Motivation, Ecological Impacts of Fragmentation, Evolution of Fragmentation Analysis; Tuchola Forest Context, Conservation Implications; Research Questions, Objectives, and Hypotheses; Structure of the Thesis.
- **Part II**: Study Area and Analytical Framework, comprising the subchapter: The Tuchola Forest Biosphere Reserve, Materials, Methods and Analytical Framework. Part III: Empirical Analyses and Synthesis, consisting of one subchapter: Synthesis, Contributions, and Future Directions
- **Part III**: Empirical Analyses and Synthesis with Chapter 4: Synthesis, Contributions, and Future Directions, and
- **Part IV**: Conclusions with the chapter Final Conclusions.

The abstract (Guide) ends with the chapters: References (4 pages) and Appendix – Full-text of 5 Publications.

Assessment of the research topic

The research topic of Sanjana Dutt's doctoral dissertation focuses on the dynamics of Scots pine forest fragmentation in the Bory Tucholskie Biosphere Reserve (RBBT) as a process analyzed on multiple spatial and temporal scales using remote sensing data (e.g., NASA LANDSAT) and products (e.g., CLC CORINE) based on the analysis of remote sensing imagery. The motivation behind Sanjana Dutt's research stems from the critical role that forests play in sustaining global biodiversity, carbon sequestration, and hydrological regulation. The author addresses the problem of the fragmentation of extensive and compact forest complexes into smaller, isolated fragments, which may be of key importance for the level of biodiversity, the health of tree stands, the risk of damage, carbon sequestration, and resistance to harmful factors.

Key motivating factors pointed out by the PhD candidate include:

- The global prevalence of 'forest edge effects' is increasing, as more than two-thirds of the world's forests currently lie within 1 km of the forest edge. This leads to increased exposure to wind, sun, and other environmental factors within the ecosystem.
- The vulnerability of temperate forests, as exemplified by the Tuchola Forest Biosphere Reserve (TFBR), is evident in the monoculture of Scots pine, which accounts for over 90% of the forest. The structure of the root system of these trees increases the forest's susceptibility to disturbances, including windfall, and the complex impact of harmful factors. This can lead to the collapse of the tree stand, especially at newly formed forest edges.
- The catastrophic windstorm (derecho) of August 11–12, 2017, which destroyed over 120,000 hectares of forest in Poland (30,000 of which were completely destroyed), highlighted the urgent need to quantify how such disturbances cause the rapid destruction of forest spatial structure and the loss of their core zones.
- The research extend the study of the links between forest structure and actual ecological processes, such as tree mortality due to stress (e.g., drought or high temperatures), as manifested by disturbances in the pigments of the assimilation apparatus. This will be achieved using advanced remote sensing and machine learning (ML) techniques.

Admittedly, the author also mentions that her research was motivated by global policies adopted in recent decades, such as the Kunming–Montreal Global Biodiversity Framework (30×30 target), REDD+ MRV protocols, and the UN Sustainable Development Goals (SDGs 6, 13, and 15) – but in the reviewer's opinion, this introduces a completely unnecessary analogy between Polish forestry and deforestation, forest degradation, and emissions resulting from deforestation. Of course, the loss of 10 million m^3 of wood in Polish forests caused by a storm (Aug. 2027) lasting several hours is not a negligible amount, but it is important to emphasize the random nature of this event and the fact that the annual biomass growth in Polish State Forests National Holding (PGL LP) alone is approximately 78 million m^3 per year.

The presented work does not directly concern biodiversity, and the doctoral student did not conduct research in this area (no mention of field research), and the assumption that an increase in the length of the forest border causes a decrease in biodiversity may be completely wrong, hence, in my opinion, referring to global policies in the abstract is unnecessary. Forest growth in Poland in recent decades has been observed both in terms of area and cumulative wood biomass. Forests in Poland cover approximately 31% of the country's area, of which almost 80% is public. Approximately 77% of forests in Poland are managed by the Polish State Forest National Holding (PGL LP).

In the Tuchola Forest area, a number of damaged tree stands remained on private land after the “storm of the century” (Aug. 11-12, 2017), which were not removed because PGL LP did not provide such assistance to other entities, being focused on its own property, which required enormous expenditure.

The reviewer wonders whether this issue of the impact of ownership structure on forest fragmentation was of interest to the doctoral student or whether it was a completely marginal problem (ReQ1).

The author of the dissertation focused mainly on analyzing the impact of extreme weather events, mainly the so-called "storm of the century" that took place on August 11/12, 2017. It is credited with causing rapid changes in the spatial structure of forest complexes in the N-S belt in the Tuchola Forest, resulting in the loss of so-called CORE areas due to windbreaks and windfalls, and in subsequent years, the removal and renewal of tree stands (forest planting). Thus, a huge increase in the edge zones of tree stands was observed, which are naturally exposed to even greater risks as they are exposed to many abiotic and biotic factors. To a large extent, such extensive damage and, consequently, the removal of completely or partially destroyed parts of the tree stands occurred due to the synergy of single-species tree stands, i.e., the massive presence of Scots pine (>90% share).

In presented dissertation, the author used well-known and proven tools from the field of landscape ecology to describe the elements that make up the landscape on the basis of so-called empirical indicators (landscape indices/metrix). The geometry of stand patch changes is based on their geometry, resulting in the calculation of parameters such as forest density zones (FAD) in stable (according to the author's assumption) cores through transition zones to highly fragmented zones of rare (open) stands (*Rare*).

The series of publications attempts to identify groups of drivers that are the main cause of forest stand fragmentation, such as: the distance of patches from agricultural land or roads, wind speed, and the parameters of the forest stand itself (age and height), constructing a statistical model of susceptibility to further degradation.

The innovative approach of the doctoral thesis consists in integrating satellite imagery (optical and microwave range of EMR) and products based on them with different spatial resolutions (Sentinel-2, Landsat-8; ALOS PALSAR) with machine learning (ML) methods, which allows for the detection of early signs of stress in tree crowns, manifested by a decrease in chlorophyll content or moisture indicators, before these changes can be clearly identified in the field.

Analyzing the above, it should be noted that the doctoral student's choice of research topic for her dissertation in the field of spatio-temporal analysis is very important, especially in the context of developing automated methods for analyzing remote sensing images and GIS spatial analyses fed with data from open repositories - with a view to determining the trend and dynamics of defragmentation of wide forest complexes on the example of the Bory Tucholskie Biosphere Reserve and the environmental effects. Admittedly, the PhD student used a considerable amount of geodata, but she did not, for example, resort to the analysis of high-resolution digital aerial orthophotomaps (RGB and NIR) or ALS LiDAR point clouds from the State Geodetic and Cartographic Resource (pzgik). The latter are widely used in scientific research, especially in the field of horizontal (2D) and vertical (3D) tree stand structure. Similarly, high-resolution satellite imagery (HR) would provide another higher (spatially) quality of geodata. An example of this is PlanetScope imagery, which is available free of charge for research purposes (academic programs). However, it is not certain whether all the details captured in HR images or LiDAR elevation models would be possible to analyze for landscape-level research due to their large quantity, but it was worth demonstrating this on a smaller area to find out.

Evaluation of the doctoral dissertation

Scientific value of the dissertation

The scientific value of the doctoral thesis submitted for review, presented in the form of an abstract and a related series of five publications, **meets the requirements for this type of scientific work,** and despite a number of critical comments and legal questions defined in the review (such as the evaluation of unpublished manuscripts submitted for review), **I assess it positively**. The dissertation stands out primarily for its different perspective on the subject of the effects of windbreaks and windfalls, which are the greatest threat to Polish forests. Even forest fires do not cause as much damage in Poland as storms. Of course, it is difficult to estimate the impact of the hydrological drought that has been going on for many years, leading to a lowering of the groundwater level and, as a result, to the emergence of complex phenomena of forest dieback and decay with the appearance of secondary pests or mass infection with mistletoe.

Based on carefully planned research, undoubtedly agreed upon many times with a supervisor who is highly experienced in both the geographical area (Tuchola Forest) and the subject matter - Supervisor, i.e. Dr. Mieczysław Kunz, prof. UMK - she proposed methodological solutions for the selection of satellite data or products of their processing, as well as classification algorithms for the assessment of spatio-temporal changes in parameters describing the fragmentation of a vast forest complex, mainly under the influence of abiotic factors.

Sanjana Dutt's doctoral thesis poses four key research questions:

1 RQ1: How have forest fragmentation definitions and measurement methods evolved, and which are most effective for temperate forest landscapes?

2. RQ2: How do fragmentation dynamics (e.g., core loss, edge expansion) and the 2017 derecho affect ecological processes across TFBR’s Core, Transitional, and Rare zones?

3. RQ3: What are the ecological impacts of fragmentation on vegetation health and ecosystem function across TFBR’s fragmentation zones?

4. RQ4: Which Sentinel-2-derived vegetation indices, integrated with machine learning, best support monitoring and prioritized conservation (e.g., core protection, transitional buffering, rare restoration) in Tuchola Forest Biosphere Reserve?

The author of the dissertation formulates five clear research objectives for the entire cycle:

Objective 1: Synthesize the evolution of fragmentation analysis to establish a methodological foundation for temperate forests (publication no. 1)

Objective 2: Quantify temporal and spatial fragmentation changes in the Tuchola Forest Biosphere Reserve (TFBR) driven by the derecho storm in 2017 (publications no. 2 and 3).

Objective 3: Assess fragmentation's ecological impacts on vegetation health and ecosystem function across Core, Transitional, and Rare zones using Forest Area Density (FAD) zoning (publications no. 2-4)

Objective 4: Develop Fragmentation Susceptibility Models using Bayesian Weight-of-Evidence (WoE) and machine learning to predict risk from drivers like cropland proximity and windstorm exposure (publication no. 4)

Objective 5: Identify sensitive Sentinel-2-derived vegetation indices (e.g., NDWI, GNDVI, EVI) using machine learning to support conservation prioritization (publication no. 5).

In order to achieve the above objectives, the author of the dissertation defines four research hypotheses (H), namely:

H1: Fragmentation increased post-2017 derecho, reducing core forest areas and expanding edge zones, as measured by FAD and MSPA.

H2: Vegetation health, assessed via NDWI, GNDVI, and EVI, is negatively correlated with fragmentation intensity, particularly in Transitional and Rare zones.

H3: Advanced landscape metrics (e.g., FAD, MSPA) and Bayesian WoE models, integrated with PALSAR and Sentinel-2 data, accurately predict fragmentation susceptibility, guiding conservation.

H4: Sentinel-2-derived indices (NDWI, GNDVI, EVI), combined with machine learning, robustly predict ecological conditions across TFBR's zones, enhancing monitoring.

Below is an assessment of the publications submitted to the series.

Publication No. 1 - *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.*

The main objective of this multi-author work was to synthesize 138 articles published between 1990 and 2025 in the field of forest fragmentation research. They set themselves the following tasks: (i) to outline changes in landscape metric groups, particularly in terms of 3-D data; (ii) to assess how the choice of data and processing methods shapes the performance of indicators; and (iii) to define limitations and good practices in reporting that would increase the comparability of results.

The authors searched databases (Google Scholar, Scopus, Web of Science) for scientific articles on remote sensing tools (LiDAR/TLS, Sentinel-2) and analytical platforms (Google Earth Engine, GuidosToolbox, R, Python), among others. The analysis of the articles was conducted around three interrelated components: geodata sources, change detection methods (time-series), and landscape pattern indicators. The literature review showed the evolution of the entire field, starting with simple metrics based on patches and edges, towards Morphological Spatial Pattern Analysis (MSPA), multiscale coherence, edge density (FAD), and vertical structure measurements (voxels/3D). The author points out that instead of proposing new landscape indicators, the scientific community should focus on harmonizing and improving existing methods for more effective use. It is crucial to introduce documentation standards (metadata), precisely describe algorithm settings, and integrate satellite data with field measurements.

The reviewer does not consider this publication No. 1 to be absolutely essential for the entire cycle, especially since it was created at the end of the cycle's preparation and, as I understand it, is still under review. It is a typical review work that does not contribute any innovative solutions or research results of the doctoral student. Of course, work no. 1 in the series is entirely theoretical, and if it had been done first (rather than last), it might have contributed many ideas and allowed for the elimination of existing shortcomings (noticed by the doctoral student), e.g., 3-D ALS LiDAR data. Therefore, the reviewer's doubts about the use of the paper (which is still under review) in the series are not very significant, as even without this paper, the series still remains coherent.

Publication No. 2 - *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.*

The main objective of publication no. 2 in the series was to analyze the temporal and spatial changes in land use and land cover (LULC) within the Tuchola Forest Biosphere Reserve (RBBT) and in three specific municipalities most affected by the storm of the century, namely Brusy, Osie, and Czersk. The authors set themselves the task of determining the scale of changes in the forest landscape caused by hurricanes and storms in 2012, 2017 (the storm of the century) and 2021. In addition, the usefulness of the Corine Land Cover (CLC) database for reliable monitoring of forest fragmentation was determined. The relationship between forest spatial patterns and ecological processes occurring after wind disasters was also assessed, establishing a reference level for the landscape before the occurrence of the most severe disturbances. The research covered the entire BT Biosphere Reserve (319,525 ha) and was carried out in the following steps: vector data from the CLC database was collected and analyzed from the following cycles: 1990, 2000, 2006, 2012, and 2018. Fifteen LULC classes were identified in the study area at the third level of CLC detail. Landscape indicators such as number of patches (NP), mean patch size (MPS), edge density (ED), mean shape index (MSI), and Shannon diversity index (SHDI). In terms of results, the analysis of CLC data showed significant changes in the structure of the forests of the Biosphere Reserve complex, i.e., a loss of 140.84 km² of forest area over the entire analysis period. The area of forest land in the regeneration phase (class: transitional woodland/shrub) increased by 726%, and in the municipality of Czersk alone by over 5000%, which was the result of destructive wind activity in 2017 and subsequent afforestation carried out until 2018 by PGL LP after clearing the damaged areas. A very clear increase in forest fragmentation was observed. The number of patches (NP), which is a landscape indicator, increased from 1,194 to 1,405, while the average patch size (MPS) decreased by 15.02%. Edge density (ED) also increased, confirming that there was a rapid breakdown of compact forest complexes. The Shannon (SHDI) index gradually increased after 2006, which paradoxically indicates greater diversity of land cover classes, resulting from the appearance of gaps, clear-cut areas, and finally windthrow areas and cleared areas prepared for new forest plantations in the landscape.

Based on the results, the authors concluded that the greatest changes in the landscape of the Tuchola Forest occurred after 2006, which is directly related to the storms of 2012 and 2017. The landscape metrics used confirmed a strong correlation between wind speed and the degree of forest fragmentation. In the authors' opinion, the Corine Land Cover database is useful for regional analyses, but higher-resolution data, such as Sentinel-2 satellite images or LiDAR data, are necessary for precise crisis management. They also point to the need to adapt conservation strategies, which should focus on strengthening forest cohesion in order to increase its resilience to future extreme events.

At this point, as a forester and geoinformatics specialist who also deals with the use of satellite images, LiDAR point clouds, and photogrammetry/image point clouds (IPC) from dense matching of aerial or UAV photos in the Tuchola Forest, the reviewer must take a position on some of the results and conclusions.

CLC databases were historically created on the basis of both topographic maps and Landsat imagery, and later editions also included medium- (MR) and high-resolution (HR) datasets (e.g., SPOT, RapidEye, and others). Thus, it can be said that the first dilemma lies in the comparability of the CLC data itself. The authors point to the need to use S-2 (ESA), but they do not use it. Perhaps it would be worthwhile to compare the latest editions of CLC with S2GLC product developed by CBK-PAN using S-2 (ESA) and ML/AI tools in the article. The second independent issue is the classification of Forest/ Non-Forest objects, which is crucial in this work. The reviewer is not entirely clear on how the authors treat clear-cuts, which have been a permanent feature of the forest landscape for at least 150 years, dedicated to Scots pine and maintaining its sustainability. This is how the Tuchola Forest was created, with large areas planted and used for clear-cutting Scots pine trees. Foresters (PGL LP) treat the area of clear-cut forest, even if prepared for regeneration (after plowing), as a forest according to the law. It is still a forest area, just like a forest nursery or a road. Here we come to the inconsistency between the classification of satellite images and SILP data/statistics from the BDL. The reviewer finds it somewhat surprising that the studies of a very known group of scientists from the University of Maryland (Hansen et al. 2013; Global Forest Change - GFC), who publish and make available global forest' loss/gain" data sets for 2000-2024, have not been used in this studies. Comparing them, for example, to the CLC dataset would shed light on classification differences, such as how long, for example, from the moment of clear-cutting (complete felling creating a gap contributing to the increase in the length of internal boundaries), this change is treated as a "loss" despite reforestation in the following year. It takes many years for the young trees to develop into a dense young forest formation, and only then do classification algorithms usually reclassify such an area as forest. Thus, the doctoral student is navigating a very complex topic without knowing how the CORINE datasets in individual editions were prepared or validated at the national level (IGiK). For example, the CLC 2018 database was based on the 2017-2018 edition of satellite images, which for the first time included full coverage of S-2 (ESA) data. Landsat imagery was used only as a supplement. An additional difficulty for the teams developing CLC 2018 was the fact that the storm occurred in August 2018 and the first cloud-free S-2 images were only available several dozen days later. The destroyed stands remained in the Tuchola Forest area for many months and longer, as there was a lack of manpower and technical resources to remove them. In many cases, it was decided to support natural regeneration by leaving mature trees (seed trees) that had somehow survived the storm. Sometimes these were small biogroups of trees that are practically impossible to detect even on S-2 images.

Finally, the reviewer has doubts about the authors' use of percentage changes instead of hectares and percentages. It is very difficult to refer to the magnitude of forest losses when only the percentage change is known. The reviewer finds it very difficult to read the graphs in Fig. 4 a, b, c, d. First of all, the Y-axis (vertical) is not described in the graph but in the figure caption as "change in area." This would imply that the changes in the three editions of the CLC 1990, 2000, 2006, and 2012 for the municipality of Brusy amounted to about 240 units for class 12 (but what is class 12? Perhaps class 312? Some kind of mental shortcut?), but what kind of units really? Is this actually a "change in area" or should it be written "Area" and the values of units in km^2?

Why are the LULC classes in Figures b, c, and d different from those in Figure 4a? The second editorial comment concerns Fig. 5 and Fig. 6. Does it really make sense to connect the lines of the graph showing the percentage changes of individual LULC classes? It symbolizes the transition between classes 324 and 411, for example. What happens to the transformation of this class if it is continuous?

The reviewer would be happy to hear the doctoral student's interpretation of the above comments and reservations at her defense (ReQ2). Values for the number of patches and their size (Table 4 – sorry, what are the units of area? For example, 1990 – 1,860,812.27 and 2018 – 1,575,127.41, but of what? If these are square meters, then one patch would be 157 hectares?).

It is a pity that the authors of this publication did not simply provide simple statistics for each municipality analyzed on the area in ha/km^2 of individual LULC classes, but instead use percentage changes or unknown units. Perhaps these are errors made by the book's editor, but then it would be worth making an errata if it is a real mistake, or perhaps the reviewer has misread something.

Publication No. 3 - *Dutt, S., & Kunz, M. (2024). Landscape metrics of the Brusy Commune before and after wind-storm: An assessment based on Landsat-8 data*

The publication presents quantitative documentation of the impact of the derecho storm of August 11/12, 2017, on the fragmentation of tree stands and changes in LULC classes as a result of the wind disaster in the municipality of Brusy (part of the Bory Tucholskie Biosphere Reserve) immediately before and after the catastrophic meteorological phenomenon, based on NASA Landsat satellite imagery. The authors focused on assessing how the storm modified spatial patterns and landscape coherence at the local level in the municipality. Overall, the classification and analyses were based on 23 cloud-free Landsat 8 (NASA) scenes from 2017 (10 images) and 2018 (13 images).

RF classification was performed using the Google Earth Engine (GEE) platform, which allowed the authors to use annual (vegetation period) median Landsat image composites. A very high overall classification accuracy of 0.92 was achieved, although it is not entirely clear to the reviewer what reference data was used and why, for example, aerial orthophotomaps were not used to validate the Landsat (NASA) classification. The methodology also did not provide a precise description of the percentage of training samples in relation to validation samples.

The Patch Analyst tool was used to calculate changes in the forest landscape structure, analyzing, among other things, the number of patches (NP), average patch size (MPS), edge density (ED), and Shannon diversity index (SHDI).

The authors found a 25.16% loss of forest area in just 12 months, with a simultaneous increase in damaged forest area of 177.52%. The number of patches (NP) increased by 38.38% over the year (from 21,375 patches to 29,579 patches), while their average size (MPS) decreased by 30.05%. Edge density (ED) increased by 67%, as predicted, indicating rapid changes in the forest interior due to wind impact. Interestingly, despite major structural changes, the Shannon diversity index (SHDI) remained largely unchanged (from 1.64 to 1.62).

According to the paper authors, the publication proved that Landsat imagery (30 m GSD with medium spatial resolution) is an effective tool for rapid and accurate mapping of the effects of natural disasters, which is crucial for crisis management in forestry.

The reviewer's comment will begin with the latest findings on the effectiveness of Landsat (NASA) in the case of natural disasters. So far, the use of satellite imagery in PGL LP has been very low. Despite the satellite operator offering images from the PlanetScope platform (3.0 m GSD, i.e., 100 times more pixels than 30 m GSD Landsat) three days after the windstorm (Aug. 11-12, 2017) the PGL LP administration was not interested in them, claiming that 3.0 m pixels were too low a resolution, and commissioned photogrammetric surveys (10-25 cm GSD), which were only completed two months after the catastrophic storm. Therefore, the authors' conclusion about the usefulness of Landsat in Polish forestry makes them seem like ”incorrigible optimists”. In most cases of possible use of satellite images, these will be examples of Sentinel-2 ESA (temporal resolution of 3-5 days instead of 16 days and spatial resolution of 10 m GSD instead of 30 m GSD).

The authors treated the clear-cuts areas as "damaged forest," which the reviewer, as a forester, cannot agree with; moreover, from a legal point of view, it is still a forest. Such areas should rather be classified as "*forests in transition*". The reviewer wonders why the authors do not clearly state the values in hectares (ha) in their next publication, for example, what was the area of lost tree stand or how many "*damaged forest*" objects there were before and after the storm. It is very difficult to read the values from Fig. 5, especially since the area is given in square kilometers and the mean patch size, surprisingly, in square meters, which is completely incomprehensible to the reviewer. For example, Forest Pre = 0.018 sq m and Forest Post = 0.006 sq m. Please explain the issue during defence (**ReQ3**).

The reviewer's own research and access to public GFC data indicate that in the Przymuszewo Forest District (which largely overlaps with the municipality of Brusy), forest loss in 2016 was typically around 360 ha per year (clear-cutting) to 368 ha in 2017 and as much as 3,500 ha in 2018. This indicates that the area of "loss" increased almost 10-fold, which is not comparable to the authors' results, but of course the reviewer refers to the area of the forest district (pl. Nadleśnictwo) and did not perform an analysis for the Brusy municipality (pl. gmina). A similar situation occurred in the Rytel Forest District, where forest loss values (GFC data) were 180, 660, and 3,700 ha (20-fold the area), respectively.

On page 27, the authors refer to examples of existing damaged forest before the 100-year storm, writing: "pre-disaster classified map (left)" on which the 2012 tornado is supposed to be visible, as the reviewer understands, in the vicinity of Trzebcina-Stara Rzeka. The reviewer cannot find this map, especially since he is referring to the 2012 tornado in the municipality of Cekcyn and not in the analyzed municipality of Brusy. A request to the doctoral student to explain this sentence during the defense (**ReQ4**).

Similarly, the authors indicate a 79.59% increase in the bare land class in the study area over the course of a year. The question is whether this applies to agriculture or some other infrastructure investments. It is difficult to comment on the results without knowing the specific areas, which are not presented in the publication in a summary table with a matrix of classification transitions between classes. Perhaps the "*bare land*" class refers to cleared logging areas, and "*damaged forest*" refers to large areas of uncleared stands still present in 2018, in addition to logging areas.

Publication No. 4 - *Dutt, S., Batar, A.K., Sulik, S., & Kunz, M. (2024). Forest ecosystem on the edge: Mapping forest fragmentation susceptibility in Tuchola Forest, Poland*

The fourth article in the series is a key element of the doctoral dissertation, fulfills the fourth research objective (O4), and verifies the third research hypothesis (H3) concerning the modeling of forest susceptibility to fragmentation under the influence of abiotic factors (wind) by analyzing the case of the Bory Tucholskie Biosphere Reserve (RBBT). It can be concluded that this work is pioneering in Poland in the field of forest fragmentation risk maps based on advanced Bayesian models. The authors note that in the era of climate change, it is no longer sufficient to determine only the effects of damage after hurricanes, so it is crucial to predict (model) the locations potentially most vulnerable to catastrophic damage. The main objectives of the study were (i) to select the best set of geodata for monitoring forest fragmentation in 2015–2020, (ii) to identify the main drivers of this process, and (iii) to develop a susceptibility model.

The original innovation of the publication is manifested, among other things, in the use of the Bayesian Weight-of-Evidence (WoE) method to assess the logarithmic probability of fragmentation based on environmental variables, as well as in the comparison of the effectiveness of global products based on microwave data (radar; SAR/PALSAR-2) with Dynamic World products (based on high-resolution Sentinel-2 ESA optical imagery).

The article uses products based on PALSAR radar imagery (25 m GSD; Global 3-class: water, Forest, Non-Forest: PALSAR 2015-2017 and Global 4-class: dense forest, non-dense forest, non-forest, water: PALSAR-2 2018-2020) and Sentinel-2 optical imagery (10 m GSD; DYNAMICWORLD V1; class "trees" with probability >0.6) and the processing was performed in the Google Earth Engine (GEE) cloud.

The analysis of forest structure fragmentation was based on the Forest Area Density (FAD) index from the GuidosToolbox software, focusing on the "Rare" (rare woody areas are cover <10% by forest) and "Patchy" (patchy 10–40% of forest cover) as indicators of intense fragmentation of previously compact stands. Fifteen variables were analyzed as explanatory variables, which, after a collinearity test (VIF), were reduced to only eight independent variables explaining the formation of fragmentation: proximity to farmland, distance from roads, tree age and height, wind speed, and vegetation moisture index.

The publication proved that products based on PALSAR (ALOS-2) microwave data are better at detecting changes in forest structure after the 2017 storm than products based on optical imagery (Sentinel-2 ESA). Using microwave data, it was shown that the share of "Rare" tree stands increased from almost 0% before 2017 to 38.68% in 2020.

The WoE model used in the analyses showed that the most important variable explaining the risk of fragmentation (damage) is the proximity of farmland (distance <200 m; WoE=0.54). In areas defined as "*transitional zones*," which often form an interface between native forest and fields, the authors propose the use of buffers and ecological corridors. These are intended to stabilize ecological processes such as water management and tree health (determined on the basis of vegetation indices describing chlorophyll), which are disrupted by so-called edge effects. According to the authors, very young forests (5–15 years old) and other stands < 9 m in height were more susceptible to fragmentation.

An increase in wind speed in the range of 25–27 m/s drastically increases the risk of fragmentation (damage; windbreaks and windfalls) and thus the creation of new edges. The high accuracy of the model was confirmed by the following indicators: AUC = 0.82 and Kappa Index = 0.68, which makes it reliable for possible planning purposes.

The authors conclude that the fragmentation of forests in the Tuchola Forest was not a random phenomenon, but resulted from the interaction of the spatial layout, i.e., the proximity of agriculturally used areas, with meteorological factors. According to its authors, the publication is of great importance for forestry practice, and they suggest the need to create buffer zones around farmland and to increase the protection of forest complexes (Core) by abandoning the creation of new roads and clearings. They also point to the need to use microwave imaging as a standard in forest monitoring after natural disasters.

Article No. 4 is undoubtedly the strongest work in the coherent series of publications by PhD candidate Ms. Sanjana Dutt, as it combines landscape ecology and forestry with modern machine learning (ML) tools, offering an original methodology for an early warning system for storms in forests. The work proves that forest vulnerability to fragmentation can and should be mapped in order to effectively manage forest resilience in the era of global climate change.

The reviewer would like to discuss whether the use of forest stand taxation parameters in the SILP database (BDL) - other than forest stand age - would strengthen the model's performance. Variables that are usually important for forest resistance are potentially: tree height (H; precise data from SILP rather than from the GLCF product), tree diameter at breast height ($d_{1.3}$), slenderness index $H/d_{1.3}$, horizontal canopy closure, forest stratification. Similarly, the use of digital height models from pzgik based on ALS LiDAR processing seems to be much more accurate than the use of global models (SRTM) with errors reaching several meters. The same applies to information on agriculture (BDOT) or roads (pzgik) as well as forest roads (LMN), which are available and are high-precision vector data. The use of a SMAP-based moisture variable with an original pixel of 36 km GSD (possible resampling to 9 km GSD) instead of, for example, moisture indicators based on S-2 ESA (20 m GSD) does not presumably give better results in a model indicating the distance of forest fragmentation risk areas located up to 200 m from crops.

In the reviewer's opinion, the direction of the storm on the night of August 11/12, 2017, was constant and ran from south to north across the study area for tens of kilometers or more, which is why even the authors classify it as a "derecho" with a constant direction. Therefore, the claim that the damage was not accidental and was an interaction with the environment (the presence of semi-cultivated areas where the wind had no obstacles to slow it down) is obviously quite obvious. The reviewer had the opportunity to observe the hurricane activity in 2012 and 2017 up close (on the same day) and also notes the "domino" effect, i.e., the intensification of the effect of trees being knocked down by successive rows of trees falling on top of each other. In the reviewer's opinion, mainly younger crops showed less damage because there were no tall trees to resist the wind. However, the authors argue that the taller the trees (H 18-26 m), the lower the risk of fragmentation (WoE = -0.33), while young, low trees (H = 9-18 m) show the highest risk (WoE = +0.36). Perhaps coincidentally, the storm mainly passed through areas of younger stands with an unfavorable slenderness ratio, separated by large areas of farmland, but from a physics point of view, taller trees offer greater resistance and are subject to uprooting and breaking in such wind conditions. Unfortunately, the authors did not present statistics based on SILP data on the structure of damaged stands (e.g., height, age class, area share before the storm), which would have made the publication even better and clearer to read.

Publication No. 5 - *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 article is the culmination of the doctoral student's research cycle, achieving research objectives O3 and O5 and verifying the fourth hypothesis (H4) concerning the use of machine learning (ML) in forecasting processes occurring in forests. The work shifts the focus of research from structural (quantitative) analyses to functional analysis (i.e., the role of the forest after the fragmentation process). The authors rightly note that forest fragmentation not only leads to changes in geometric structures, but also drastically affects the next 10 years by changing ecological processes: from water management to the health of trees, i.e., their physiology. The research was carried out in the Bory Tucholskie Biosphere Reserve for the periods 2016, 2020, and 2024, which allowed for the capture of the long-term effects of, above all, the storm of 2017 (approx. 80,000 ha of destroyed tree stands), but also (relatively) small-scale incidents in 2012 (tornado 500 ha) and 2021 (approx. tornado 1,000 ha). The methodological innovation introduced by the authors of the publication consists in the use of the so-called FAD - Foreground Area Density zoning of forest areas, dividing them into zones: Core (forest cover ≤90% in the zone), Transitional (forest cover ≤40–60% in the zone) and Rare (forest cover ≤10% in the zone). In addition, the methodology includes machine learning (ML) algorithms such as Extra Trees (ET) and LightGBM. It is worth noting that the authors made an effort to examine the performance of the algorithms. They used partial dependence plots (PDP) and permutation importance to explain how selected vegetation indicators (VI's) explain events in different forest zones. Sentinel-2 ESA imagery was merged with current forest management data (Forest Data Bank - BDL) on degradation, humidity, habitat type, and tree age.

The analyses showed that the structure of the forest directly affects its life processes, i.e., that in the Rare zones, the NDRE and GARI vegetation indices were the most sensitive detectors of incipient chlorophyll disturbance processes in pine crowns, as exposure to climatic factors has the strongest impact on the edges of forests, especially those of small complexes.

It has been proven that Core forest zones exhibit relatively stable water management, while Rare and Transitional zones suffer from strong fluctuations in humidity (measured by NDMI and NDWI indices), which is determined by high forest edge density indices. The authors also confirmed that in highly fragmented zones (Rare), young regeneration spectrally resembles the crowns of mature older stands, which obviously creates a risk of misinterpreting the age class of the forest when, for example, the Canopy Height Model (CHM) based on ALS LiDAR data is not used.

Paper No. 5 in the series proves that free satellite imagery (Sentinel-2 ESA) combined with a mathematical model can be the beginning of an early warning system for forest dieback and decay, and that this is a scalable approach that can be transferred to other temperate and boreal ecosystems. Article No. 5 concludes the narrative of the entire dissertation, combining elements of landscape ecology (mainly forest-agricultural landscapes) with practical satellite monitoring. It confirms that modern satellite remote sensing is a tool capable of tracking changes in near real time over large areas.

Undoubtedly, the inclusion of data from the ALS LiDAR campaign from 2012-2015 and later, e.g., 2023, would have made it possible to avoid potential problems with distinguishing tree stand development classes (spectral similarities) or would have provided more precise data, e.g., on canopy roughness and variability, its horizontal closure and penetration index, not to mention the locations of individual crowns and the determination of spatial indicators based on proximity. ALS LiDAR data in the form of point clouds and their processing products such as DTM and DSM are publicly available and free of charge, and are characterized by high accuracy.

Undoubtedly, the use of Sentinel-2 images, despite their significantly better spatial resolution than Landsat-8/9 (NASA) imageries, was a step in the right direction, but in a situation of high fragmentation and the presence of single biogroups, so-called seed trees or ecological trees, in areas of destroyed tree stands, detection is not possible. In this situation, it is worth using HRS images such as PlanetScope (3.0 m GSD) or VHRS (GSD < 1.0 m) such as WorldView-2/3 (0.5/0.3 m GSD PAN; 1.2–2.0 m GSD MS) or KOMPSAT, which was already demonstrated in 2018 in the reviewer's publications. The VHRS images have much greater potential in detecting various degrees of tree stand damage, and with the support of elevation models, the prediction of damage classes is high. Thus, it can be concluded that the use of CHM (LiDAR)-supported digital aerial orthophotomaps would give even better results, although the doctoral student dealt in most cases with the landscape of the Biosphere Reserve rather than individual trees, which may to some extent explain the approach she took.

General comments

The reviewer's overall assessment of the dissertation is based on many factors, including

- a very apt choice of topic that is becoming increasingly important in PGL LP (such research topics have been commissioned in the past and are still of interest to forest administration, but also to PKP);
- the doctoral student's knowledge in other natural sciences beyond geoinformatics,

i.e., in hydrology;

- well-planned scientific research and its timing and thematic scope;
- use of GIS tools, a range of open geodata, and machine learning (ML) for research;
- mastering difficult analytical (statistics) and geoinformatics (GIS software) tools;
- quickly learning the basic natural conditions shaping forest ecosystems in Central Europe;
- introducing a new perspective of GIS and remote sensing analyses in landscape ecology research using a set of microwave and optical data and a range of vegetation indicators;

Conclusion

After analyzing the submitted dissertation, which has a solid methodological basis in the use of remote sensing data and products, ML modelling algorithms, GIS spatial analysis, **I can unequivocally state that the doctoral student's contribution to Earth sciences** related to forest landscape ecology shaped by extreme wind phenomena, as well as interactions with anthropogenic factors shaping the LULC system and the age-spatial structure of tree stands, **is significant.**

The **doctoral dissertation** presented by **Ms. Sanjana Dutt** is an **original solution to an important problem in scientific research** on the risk of forest complex fragmentation and the prediction of variables that best explain the location of endangered areas and the consequences of gale-force winds on the health of surviving forest fragments in the context of intensifying climate change in Poland.

The reviewer has **no doubts about the doctoral student's knowledge and independence in conducting scientific research** in the field of landscape ecology, GIS spatial analysis, classification of large data sets in cloud computing, geodata modeling, including synthesis of results, in the field of Earth and Environmental Sciences.

I hereby conclude that the **doctoral dissertation by Ms. Sanjana Dutt**, supervised by her advisor, **Dr. Mieczysław Kunz**, **professor** at Nicolaus Copernicus University in Toruń, **meets the requirements** for doctoral dissertations set out in Article 187 of the Act of July 20, 2018, on Higher Education and Science (consolidated text: Journal of Laws of 2024, item 1571, as amended) - therefore, I request the Council of Earth and Environmental Sciences of the Nicolaus Copernicus University in Toruń to admit the author to the next stages of the doctoral procedure in the field of exact and natural sciences in the discipline of Earth and environmental sciences.

Signed by /
Podpisano przez:

Piotr Wężyk

Date / Data:
2026-01-12 23:51

Dr. Piotr Wężyk, prof. URK