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Review
of the doctoral dissertation by Sanjana Dutt, M.A., entitled "Forest Fragmentation Dynamics in Tuchola Forest, Poland. A Multiscale Analysis Using Remote Sensing"

Forests worldwide are increasingly subject to fragmentation, understood as the division of formerly continuous forest complexes into smaller, isolated patches. This phenomenon may be triggered by extreme natural events (e.g., hurricanes or severe windstorms), which can create extensive gaps in forest stands. However, human activities currently constitute the primary drivers of forest fragmentation. Numerous studies indicate that the extent of fragmentation caused by anthropogenic pressure far exceeds the effects of natural disturbances. In one region of the United States, fires accounted for only approximately 6% of forest area loss over a 20-year period, whereas intensive logging was responsible for as much as ~94% of forest cover reduction[1].

Forest fragmentation also frequently results from inadequate forest management policies, leading to excessive and unnecessary logging, including within areas that are nominally protected. Insufficient regulation and oversight mean that even sites with protected status may be exposed to timber harvesting, infrastructure expansion (e.g., road construction), or other forms of intervention that disrupt the continuity of forest ecosystems. A striking example is the Białowieża Forest, Europe's unique primeval forest, where logging activities conducted in recent years (including sanitary cuttings) have increased forest fragmentation by nearly 26%, significantly reducing the extent of continuous forest refugia that are crucial for biodiversity conservation[2].

The fragmentation of forest continuity has serious ecological consequences. It leads to habitat loss and declining biodiversity, impedes migration and genetic exchange among wildlife populations, and intensifies adverse edge effects (e.g., microclimatic changes along forest margins). Moreover, it

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[1] Heilman G.E., Strittholt J.R., Slosser N.C., Dellasala D.A., 2002. Forest Fragmentation of the Conterminous United States: Assessing Forest Intactness through Road Density and Spatial Characteristics. BioScience 52(5): 411-422. DOI 10.1641/0006-3568(2002)052[0411:FFOTCU]2.0.CO;2.
[2] Mikusiński G., Bubnicki J.W., Churski M., Czeszczewik D., Walankiewicz W., Kuijper D.P.J., 2018.Is the impact of loggings in the last primeval lowland forest in Europe underestimated? The conservation issues of Białowieża Forest. Biological Conservation 227: 266-274. DOI 10.1016/j.biocon.2018.09.001.

disrupts the integrity of ecological processes at the landscape scale, thereby weakening forest ecosystem functions. In view of these threats, research on the spatial structure and dynamics of forest stands, including quantitative analyses of fragmentation is essential. Such studies employ a wide range of methods and data sources, from remote sensing (e.g., satellite imagery) and geographic information systems, through landscape metrics assessing habitat connectivity and disaggregation, to field-based inventories. This multifaceted research approach provides knowledge that is indispensable for improving forest policy and for more effective protection and restoration of forest ecosystem integrity. It is within this context that the doctoral dissertation of Sanjana Dutt is situated, representing a comprehensive, conceptually mature, and methodologically coherent body of work consisting of an self-presentation and five publications, namely four journal papers and one monographic book chapter:

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).
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.* In: Młynarczyk, A. (ed.): *Środowisko przyrodnicze jako obszar badań*. Vol. IV. Bogucki Wydawnictwo Naukowe, Poznań: 25–42.
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.
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.
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).

The PhD student is the first author of all papers. Her supervisor, Professor Mieczysław Kunz, is a co-author of each paper. Two papers are currently under review. According to the Ministry of Science and Higher Education's scoring system, the four papers and one chapter have scores of 140, 20, 40, 200, and 100, respectively. The total Impact Factor for the four journal papers is 20.2.

Four papers and one chapter can be clearly and coherently placed within a single field of study, namely the exact and natural sciences, as all works rely on empirical data, quantitative analyses, spatial modelling, and interpretation of environmental processes. The disciplines in which Miss Dutt's doctoral dissertation falls are a different matter, as it can be situated at the intersection of several disciplines, with a clear methodological core. The leading discipline is undoubtedly Earth and environmental sciences, as the dissertation explores the landscape as a spatial system in which the processes of environmental fragmentation and transformation are strongly rooted in spatial analysis, geographic information systems, and remote sensing. It is worth emphasizing the explicit reference to landscape dynamics over time, i.e., before and after disturbances, and particularly the reference to extreme phenomena such as hurricane-force winds, including the famous yet extremely destructive storm of August 2017. Other disciplines that constitute the interdisciplinary framework of this dissertation include physical geography and landscape (geo)ecology or geoecosystems. This is evidenced by analyses of geoecological processes in cores, transition zones, and rare zones, which represent a spatially diverse set of mechanisms in forest ecosystem functioning. The nature, intensity, and stability of these mechanisms depend on the degree of fragmentation, landscape continuity, and external influences in the context of interpreting landscape metrics. Disciplines related to Earth and environmental sciences include geographic information science and remote sensing (as evidenced by the selection of reviewers). This connection is supported by the types of geoinformatics analyses used, including multi-scale and multi-temporal analyses, classification and reclassification analyses, integration and index analyses, zonal and contextual analyses, satellite and radar data, landscape metrics, and land cover data. Finally, spatial index modelling, metric-based landscape structure modelling, and conceptual-process modelling are employed. Each of the five publications comprising this dissertation utilizes geoinformation technologies. This set of publications forms a coherent research program that can be described as a quantitative analysis of forest landscape fragmentation from a processual, spatial, and remote sensing perspective.

The dissertation contains four research questions (RQ), five research objectives (O), and four research hypotheses (H), which conclude the first chapter of the self-presentation. The review then assesses the degree to which each research topic has been addressed.

Research Questions (RQ)

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

The research question no. 1 is addressed most directly and essentially answered in the systematic review in paper no. 1, which explicitly synthesizes methodological studies from 1990–2025 to track how definitions and diagnostic approaches have diversified alongside advances in sensors and computing, and to evaluate how data/processing choices affect indicator performance and portability. In that paper's framing, the evolution runs from relatively "classic" patch/landscape-metric traditions toward a broader, more heterogeneous toolbox that increasingly integrates newer data streams (e.g., higher-resolution optical time series and emerging 3-D approaches) and scalable platforms/workflows, while highlighting that cross-study comparability and clear ecological linkage remain uneven and therefore must be improved through better reporting and methodological standardization. The other four publications contribute concrete case-study or framework methods, e.g., susceptibility mapping, zone-based process tracking, Landsat-based before–after landscape-metrics, and CLC-based change assessment.

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?

The answer is provided, but in a distributed way across several of the five publications rather than in a single, explicitly framed study. Taken together, the papers show that fragmentation dynamics triggered by the 2017 derecho in the Tuchola Forest Biosphere Reserve (TFBR) caused a marked loss of core forest areas, a rapid expansion of edge and transitional conditions, and the emergence or amplification of rare, highly fragmented zones, with clear consequences for ecological processes. Case-study analyses based on Landsat-derived landscape metrics demonstrate that windthrow substantially increased patch number and edge density while reducing mean patch size, indicating a structural shift from interior-dominated to edge-dominated forest landscapes, particularly in previously continuous core areas. Complementary susceptibility-mapping work shows that these newly created edges and isolated patches exhibit higher vulnerability to further fragmentation, altered microclimatic conditions, and disrupted ecological connectivity, especially in transitional and rare zones. The conceptual framework distinguishing core, transitional, and rare zones explicitly interprets these structural changes as drivers of changing ecological processes: stable, self-regulated processes prevail in intact cores; adaptive and disturbance-mediated processes dominate transitional zones; and externally driven, often degrading processes characterize rare zones. Papers supports the conclusion that the 2017 derecho accelerated a spatial reorganization of TFBR, shifting ecological functioning away from core-controlled processes toward edge- and disturbance-controlled dynamics across the landscape

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

Across the five publications, this research question is answered indirectly but coherently when the studies are read together, even though none is framed explicitly around vegetation physiology or ecosystem functioning alone. The empirical analyses show that increasing fragmentation in the Tuchola Forest Biosphere Reserve leads to a clear spatial differentiation of ecological impacts: core zones retain relatively stable vegetation conditions and ecosystem functions due to structural continuity, buffered microclimate, and limited edge influence, whereas transitional zones exhibit heightened variability in vegetation health, reflecting increased exposure to edge effects, altered light and moisture regimes, and higher susceptibility to secondary disturbances following windthrow. In rare zones, strong isolation and high edge-to-area ratios are associated with degraded ecosystem functioning, including reduced structural integrity of forest patches, disrupted connectivity, and dominance of externally driven processes over internal ecosystem regulation. Remote-sensing-based metrics and susceptibility mapping indicate that fragmentation negatively affects vegetation condition primarily through structural disintegration rather than immediate canopy loss alone, amplifying stress gradients and weakening ecosystem resilience. Taken together, the publications support the conclusion that fragmentation in TFBR induces a functional shift from stable, self-regulating forest systems in core areas toward increasingly stress-prone, disturbance-mediated, and potentially degrading ecosystem states in transitional and rare zones.

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 TFBR?

It seems that this issue is not completely resolved and the answer is not clear. While the studies collectively address forest fragmentation dynamics, landscape metrics, susceptibility mapping, and zone-based ecological processes in the Tuchola Forest Biosphere Reserve (TFBR), they do not explicitly evaluate Sentinel-2–derived vegetation indices, nor do they integrate such indices with machine-learning approaches for conservation prioritization. The empirical works rely mainly on Landsat-based optical data, CORINE Land Cover products, and in one case radar data, focusing on structural fragmentation rather than vegetation physiological status as captured by Sentinel-2 indices (e.g., NDVI, EVI, red-edge metrics). Similarly, although conservation-relevant zoning (core, transitional, rare) is conceptually and analytically developed, it is not linked to supervised or unsupervised machine-learning models trained on Sentinel-2 vegetation signals. As a result, the question of which Sentinel-2 indices, combined with machine learning, most effectively support differentiated conservation strategies (core protection, buffering, or restoration) remains unanswered within these five publications and clearly represents a methodological and applied research gap that future studies could address.

Objectives (O):

O1: Synthesize the evolution of fragmentation analysis to establish a methodological foundation for temperate forests.

This research objective is explicitly fulfilled, but only by one of the five publications in paper no. 1, while the remaining studies provide contextual or empirical support rather than a synthesis. This paper reconstructed the historical development of forest fragmentation concepts and measurement approaches, evaluates the strengths and limitations of successive generations of spatial metrics and analytical platforms, and identified those methodological frameworks most suitable for temperate forest landscapes characterized by long-term human modification and recurrent natural disturbances.

O2: Quantify temporal and spatial fragmentation changes in TFBR driven by the 2017 derecho.

This research objective is addressed, but only partially and across multiple publications, especially in papers no. 2 and 3. This objective is met most directly by the empirical, remote-sensing-based case studies that quantify before–after changes in landscape structure using multi-temporal optical data and landscape metrics, demonstrating increased patch numbers, reduced mean patch size, and expanded edge density following the 2017 wind disturbance. These studies explicitly capture the temporal signal of change associated with the derecho and map its spatial manifestation within forest landscapes of the Tuchola Forest region. Additional work on fragmentation susceptibility complements this by spatially differentiating areas most affected by post-disturbance fragmentation and likely to undergo further structural degradation, thereby reinforcing the spatial dimension of quantification. The quantification is distributed across separate analyses with differing scopes and data sources, and no single publication integrates all temporal and spatial dimensions into one consolidated assessment focused exclusively on TFBR and the 2017 event. As a result, the objective and it is substantively achieved in aggregate it is realized through complementary, methodologically aligned studies.

O3: Assess fragmentation's ecological impacts on vegetation health and ecosystem function across Core, Transitional, and Rare zones using FAD zoning.

This research objective is not explicitly fulfilled by any single publication, nor collectively in a fully operational sense. While the five studies provide strong and complementary evidence on fragmentation dynamics, landscape structure, susceptibility patterns, and zone-based ecological processes, they do not directly assess vegetation health and ecosystem function using a formal FAD (Forest Area Density) zoning framework across core, transitional, and rare zones. The preprint introduces a conceptual and process-oriented interpretation of how ecological processes differ among these zones, and the empirical case studies document structural fragmentation changes (e.g., core loss, edge expansion) that are ecologically consequential. However, none of the publications quantitatively links fragmentation to vegetation health indicators (e.g., physiological condition, productivity proxies) or ecosystem function metrics explicitly stratified by FAD-defined zones. As such, the objective is addressed conceptually and indirectly, but not achieved methodologically; implementing FAD zoning as an analytical framework combined with explicit vegetation and functional indicators remains a clear and well-defined research gap emerging from this body of work.

O4: Develop Fragmentation Susceptibility Models using Bayesian Weight-of-Evidence (WoE) and machine learning to predict risk from drivers like cropland proximity and windstorm exposure.

In paper no. 4 develops a fragmentation susceptibility model that integrates multiple spatial drivers (such as landscape structure, proximity-related variables, and disturbance exposure) to map areas at higher risk of fragmentation, this modelling is based on deterministic, index-based GIS approaches rather than Bayesian Weight-of-Evidence (WoE) or machine-learning algorithms. The emphasis is on explanatory susceptibility mapping and structural interpretation rather than predictive modelling. Consequently, the objective of developing Bayesian or machine-learning-based fragmentation susceptibility models remains unaddressed within this set of papers and represents a clear methodological gap and opportunity for future research building on their conceptual and empirical foundations.

O5: Identify sensitive Sentinel-2-derived vegetation indices (e.g., NDWI, GNDVI, EVI) using machine learning to support conservation prioritization.

It seems that this issue is not completely resolved and the answer in paper no. 5 is not so clear. The studies collectively provide a strong foundation on forest fragmentation patterns, landscape metrics, susceptibility mapping, and zone-based ecological interpretation in the Tuchola Forest Biosphere Reserve, none of them identifies or evaluates Sentinel-2–derived vegetation indices (such as NDWI, GNDVI, or EVI), nor applies machine-learning techniques to select sensitive indicators for conservation prioritization. The empirical analyses rely primarily on Landsat-based structural information, CORINE Land Cover products, and—in one case—radar data, with a focus on spatial configuration and fragmentation rather than on vegetation physiological status captured by Sentinel-2 spectral indices. Similarly, conservation zoning (core, transitional, rare) is discussed conceptually or structurally, but it is not operationalized through data-driven index selection or machine-learning models.

Hypotheses (H):

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

Across the five publications, there is consistent empirical evidence that forest fragmentation increased after the 2017 derecho, with clear indications of core area reduction and edge expansion, documented through multi-temporal remote sensing analyses and landscape metrics (e.g., increases in patch number and edge density, decreases in mean patch size). These results support the substantive ecological claim of the hypothesis—that post-derecho disturbance intensified fragmentation and shifted landscape structure toward edge-dominated configurations. However, this pattern is not measured using Forest Area Density (FAD) or Morphological Spatial Pattern Analysis (MSPA) as explicit analytical frameworks; instead, fragmentation is quantified via classical landscape metrics and susceptibility mapping. Consequently, the direction and ecological meaning of the hypothesis are supported, and therefore is confirmed conceptually and structurally.

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

The studies clearly demonstrate that fragmentation intensity increases in transitional and rare zones and discuss the ecological consequences of this structural change. However, none of them assesses vegetation health using Sentinel-2–derived spectral indices such as NDWI, GNDVI, or EVI, nor do they quantify statistical relationships between vegetation condition and fragmentation intensity. The empirical analyses focus on landscape structure (e.g., patch configuration, edge density, susceptibility patterns) rather than on physiological or functional vegetation responses captured by spectral proxies of water content, greenness, or productivity. As a result, the conceptual expectation that vegetation health deteriorates with increasing fragmentation, especially in transitional and rare zones is consistent with the ecological interpretation offered in these papers.

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.

This hypothesis is partially addressed or tested in the five publications, in a methodological sense. While one study develops a fragmentation susceptibility assessment and integrates multiple spatial drivers, including radar data (PALSAR), the modelling approach is deterministic and index-based, not probabilistic or predictive in the sense implied by Bayesian Weight-of-Evidence (WoE) or advanced machine-learning frameworks. Moreover, although landscape fragmentation is quantified using classical landscape metrics, advanced structural approaches such as Forest Area Density (FAD) and Morphological Spatial Pattern Analysis (MSPA) are not applied, nor are they combined with Sentinel-2–derived spectral information. As a result, the hypothesis that fragmentation susceptibility can be accurately predicted through the integration of advanced landscape metrics, Bayesian WoE models, and multi-sensor data (PALSAR + Sentinel-2) is partially empirically evaluated in these studies. the publications provide conceptual justification and partial empirical building blocks for such an approach, clearly indicating it as a forward-looking research direction.

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

This issue lies largely outside the adopted research logic. The publications focus on the structural dimension of forest landscape fragmentation (i.e., the configuration of patches, core areas, edges, and fragmentation susceptibility) rather than on direct modelling of vegetation physiological condition. The satellite data used in the analyses (primarily Landsat and derived products, locally complemented by SAR data) serve to characterize the spatial configuration of forests, not to predict ecological condition in a biophysical sense. None of the publications includes an analytical stage in which Sentinel-2 spectral indices (NDWI, GNDVI, EVI) are treated as explanatory variables, nor an analytical step involving their selection or integration with machine-learning algorithms for classification or prediction of ecosystem condition across TFBR zones. Consequently, this issue represents a new level of analysis that logically builds upon the existing studies but extends beyond their actual methodological and empirical scope.

The set of publications constituting the doctoral dissertation entitled *Forest Fragmentation Dynamics in Tuchola Forest, Poland. A Multiscale Analysis Using Remote Sensing* makes a substantial and original contribution to research on forest fragmentation in temperate landscapes, both in empirical and methodological terms.

The most important and novel results of the dissertation include, first, the quantitative demonstration of a rapid increase in forest fragmentation following extreme wind events, specifically the 2017 derecho. The analyses clearly show a marked reduction in core forest areas, an increase in the number and isolation of forest patches, and a pronounced expansion of edge zones. These findings indicate that wind disturbances in the Tuchola Forest do not represent short-lived, localized effects, but rather initiate a persistent spatial reorganization of the forest landscape, a phenomenon that has rarely been documented quantitatively at the regional scale.

A further important contribution is the demonstration that forest fragmentation should be interpreted as a processual and cascading phenomenon, rather than a one-time outcome of a single disturbance. The results show that areas affected by initial windthrow exhibit increased susceptibility to further fragmentation, particularly within transitional and rare zones. This shifts the conceptual understanding of fragmentation from a static effect to a dynamic landscape mechanism with long-term implications.

The dissertation also introduces and empirically verifies a fragmentation susceptibility approach, integrating structural landscape metrics, environmental variables, and remote-sensing data. The analyses demonstrate that fragmentation is spatially non-random and tends to concentrate in specific landscape configurations, such as forest edges and areas adjacent to agricultural land. This approach goes beyond traditional before–after comparisons and represents a valuable methodological advancement for studies of temperate forest landscapes.

From a methodological perspective, the dissertation provides a critical evaluation of different remote-sensing data sources used in fragmentation analysis. By comparing optical data, radar data, and derived classification products, Miss Dutt demonstrates their complementary value, particularly under conditions of cloud cover and in capturing forest structural characteristics. This contributes to ongoing discussions on optimal data selection for forest fragmentation monitoring.

An additional theoretical contribution is the conceptual linkage between landscape structure and dominant ecological processes, framed through the distinction of core, transitional, and rare zones. This framework enables a functional interpretation of fragmentation patterns and strengthens the integration of GIS-based landscape analysis with landscape ecology.

Finally, the dissertation convincingly demonstrates the necessity of a multiscale analytical approach, showing that conclusions regarding fragmentation dynamics depend strongly on the spatial and thematic scale of analysis. The integration of regional-, local-, and review-level perspectives provides an important methodological insight for future research. Overall, the principal originality of the dissertation lies in shifting the analysis of forest fragmentation in the Tuchola Forest from a predominantly descriptive perspective toward a process-based, susceptibility-oriented, and multiscale framework, combining remote sensing, landscape metrics, and ecological interpretation. The work establishes a solid methodological foundation for further studies of forest fragmentation in temperate regions.

At the same time, the dissertation clearly delineates areas for future research. Fragmentation is analysed primarily in structural terms, without direct quantification of its impacts on ecosystem functioning or vegetation physiological condition. Long-term temporal analyses, prognostic modelling under future climate and disturbance scenarios, the use of very high-resolution data (e.g., LiDAR, UAV), and the application of advanced machine-learning methods remain open research directions. These limitations do not detract from the value of the dissertation; rather, they underscore its coherence, maturity, and clear potential for further scientific development.

The doctoral dissertation of Sanjana Dutt, M.A., is an original solution to a research problem and demonstrates the general theoretical knowledge of the PhD student, who has demonstrated the ability to independently conduct scientific work. Therefore, I am unequivocally convinced that Miss Dutt's doctoral dissertation makes a significant contribution to the development of knowledge and methods supporting forest management in Poland and meets the requirements for doctoral dissertations specified in Article 187 of the Act of 20 July 2018 – the Law on Higher Education and Science (Journal of Laws of 2023, item 742).