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QUANTIFYING FOREST DISTURBANCES AND LANSCAPE LEVEL OVER HALF A CENTURY USING COLD WAR SPY SATELLITE AND CONTEMPORARY IMAGERY. CASE STUDY PECINEAGU WATERSHED, ROMANIA

Ioana A. NICOLAE[1] **Mihai D. NIȚĂ**[1]

Abstract: *This study examines disturbances in the Pecineagu watershed forests over the last 50 years. The primary objective of this study is to comprehensively assess the intensity and consequences of canopy disturbances in the Pecineagu watershed forests over the past half-century. Utilizing meta-analysis and advanced remote sensing techniques, including satellite imagery from Corona Spy, Landsat, and Sentinel-2, we identified significant changes in forest cover and structure. The analysis revealed 142 hectares of disturbed forest between 1986 and 1996, with a notable portion undergoing clear-cutting and afforestation. Despite these disturbances, our findings show high forest connectivity and low fragmentation, predominantly in the dominant forest layer. However, two areas, i.e. Berevoiu – Valea Coltilor and Manastire – Valea Comisului, experienced substantial fragmentation in different periods, indicating variable impacts across the watershed. These results underscore the importance of continuous monitoring and sustainable forest management to maintain forest connectivity and minimize fragmentation. The study also highlights the need for accurate data recording in forest management plans for effective resource management, offering crucial insights into forest conservation strategies amid environmental changes.*

Key words: *ecosystem services, forest disturbances, remote sensing, fragmentation, Pecineagu watershed.*

[1] Transilvania University of Brașov, Faculty of Silviculture and Forest Engineering, Șirul Beethoven 1, 500123 Braşov, Romania;
Correspondence: Ioana Alexandra Nicolae; email: ioana.nica@unitbv.ro.

1. Introduction

The impact of human activities on forest ecosystems has become a central concern in ecological research amid escalating global environmental challenges [32. Forests are critical for ecosystem functioning, carbon storage, climate regulation, and biodiversity, yet they face significant long-term changes due to anthropogenic influences [7, 21]. These influences create enduring legacies that shape ecosystem structure and functioning, influencing management practices for centuries [10]. However, the links between historical and contemporary land management practices remain poorly understood, largely due to limited historical data, including satellite imagery [23].

As forests become increasingly vulnerable to climate change, it is imperative that forest management adopts sustainable measures that are ecologically and economically viable, socially integrated, and adapted to local needs and traditions [6]. Within the framework of sustainable development and against the backdrop of climate change and biodiversity loss, conserving and wisely utilizing ecosystem services is crucial [9, 34]. Forests play a key role in combating climate change as they are vital for climate regulation and life support, they absorb and store significant amounts of carbon dioxide in trees, vegetation and soil, and release oxygen [13]. They also influence temperature, precipitation, and weather patterns and provide habitat for numerous plant and animal species essential for ecosystem stability and resilience [27].

Emerging forest-related policies reflect the multifaceted nature of ecosystem services, addressing roles in climate change mitigation, nature conservation, and the bioeconomy [16, 33]. In Romania, the approach to forest ecosystem services has been shaped through regulation and the formulation of forest management plans [4, 22]. Historical forest management, particularly from 1864 to the First World War, focused on agriculture, resulting in significant forest area loss. Efforts between the world wars were aimed at afforestation and increasing forest cover [28]. Post-World War II Soviet policies led to extensive clear-cutting and the planting of fast-growing species, peaking conifer cover at 31% in the mid-1980s [18]. The transition to a market-based economy post-1990 marked a shift towards sustainable forest management with an emphasis on biodiversity protection [1, 8, 29]. However, forest land restitution post-1991 also led to both legal and illegal logging due to new owners' desire for profit or fears associated with insecure ownership [2, 9, 15].

Despite growing recognition of the ecosystem services approach, its application in Romanian forestry studies is limited. This gap is due to insufficient research on ecosystem services and minimal translation of international research to local contexts. Increased awareness of forest ecosystem importance and the need for funding in the forest sector and protected areas is critical for sustainable management [25]. Forest disturbances, both natural and human-induced, play a pivotal role in forest succession, maintaining ecological balance and stability [11, 20].

Understanding the location, timing, and extent of these disturbances is essential for developing effective mitigation strategies [3, 5, 14, 19].

Previous studies have predominantly focused on mapping forest clear cuts using remote sensing over limited areas or plot-level studies on various ecosystem services aspects [12, 15, 26]. This study leverages remote sensing analysis, combining historical Cold War spy satellite imagery with contemporary Landsat and Sentinel-2 data, and forest management plans in the Pecineagu watershed. Remote sensing offers accurate, relevant data on forest environments, enabling sustainable management to maintain connectivity and minimize fragmentation [30]. Continuous monitoring with accurate data can develop more effective forest management and biodiversity conservation strategies [17].

This research aims to expand our understanding of human impacts on forest continuity, habitat suitability for species, and overall sustainability. It questions the sustainability of current forest management practices in Romania across environmental, economic, and social dimensions. By integrating historical and contemporary satellite imagery with data on human and natural disturbances recorded in management plans, this study seeks to understand the long-term impact of these disturbances in the Pecineagu watershed.

The primary objective is to quantify forest disturbances over half a century using a meta-analysis of management plan data and digital analysis of disturbances. The secondary objective is to perform a comprehensive landscape analysis using various algorithms. This multifaceted approach will characterize changes in forest structure over more than 50 years, offering an objective assessment of forest management sustainability. Ultimately, this study aims to provide a thorough evaluation of the intensity of human interventions and the consequences on forest structure and ecosystem services, contributing to the development of sustainable forest management strategies.

2. Materials and Methods

2.1. Study Area

Our study area is located in the upper part of the Dâmbovița Valley (Figure 1), upstream of the Pecineagu Dam, within the administrative area of Rucar commune, Arges County, a representative area in Romania for the protection of local biodiversity and water resources. Geographically, the area is located in the Southern Carpathians, subgroup of the Fagaras Mountains, Iezer - Papusa Massif.

The average altitude where most of the stands are located (61%) is between 1,200 and 1,750 m. The predominant geomorphological unit is the slope with an average gradient between 30 and 45 degrees (81%), the terrain configuration being undulating. In terms of forest vegetation, the main species is spruce, in pure stands and in mixtures. The stands in the study area are intended to protect the slopes of the watersheds feeding the Pecineagu reservoir, and those of the alpine hollow to protect the forest boundary. The entire area falls into functional group I, of which 53% are forests with water protection functions and 45% forests with land and soil protection functions.

To monitor changes in the Pecineagu watershed forest ecosystem over the past 50 years, we utilized a combination of historical and contemporary data sources. These included forest management plans and satellite imagery, which together provided a comprehensive view of forest disturbances over time.

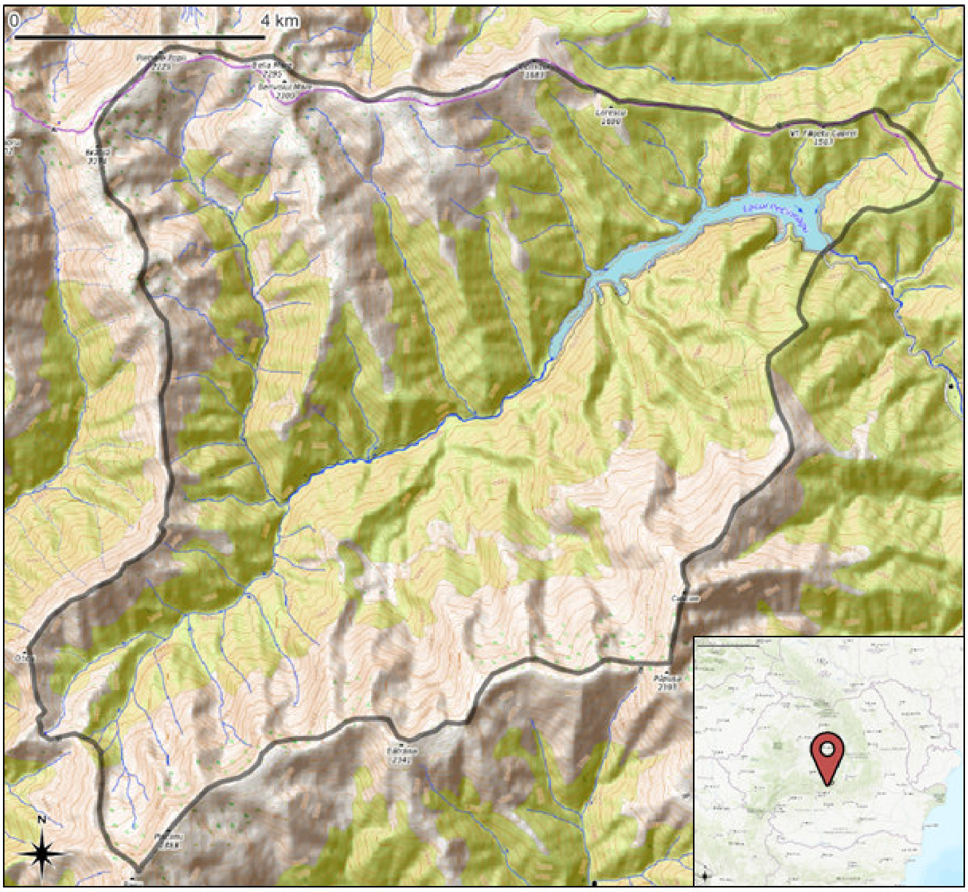


Fig. 1. *Map of Pecineagu watershed ecosystem*

2.2. Data Used for Mapping Forest Disturbances

Forest management plans were obtained from U.P. IV Tamas and U.P. V Izvoarele Dâmbovitei for the years 1986 and 1996, as well as from private forest owners after 2000. These plans, available in GIS format, detailed records of forest cover loss due to forestry activities such as clear-cutting and thinning, as well as natural processes like windthrow and forest fires (Table 1).

For historical data, we utilized Corona images from 1970, which offered high-resolution (2 meters per pixel) insights into past land use and forest conditions. These images were rectified using Structure from Motion technology, allowing for accurate spatial analysis. Contemporary data were sourced from Landsat imagery spanning 1985 to 2012, providing medium resolution (30 meters) data available from the Global Land Analysis & Discovery platform. Additionally, Sentinel-2 data with high spatial resolution (10 to 60 meters) were used to monitor current forest disturbances. This data, accessible via Google Earth Engine, were analyzed using the Relative Radiometric Normalization Index (RRNI) to create composite images for detailed assessment.

Data sources Table 1

	1970	1980	1990	2000	2010	2020
State management plans	■	■	■			
Private owners' management plans				■	■	■
Corona	■					
Landsat Legacy		■	■	■	■	■
Sentinel 2						■

2.3. Long-Term Forest Disturbances Quantification

To provide a thorough evaluation of forest disturbances, we combined data from forest management plans and satellite imagery. Manual digitization of historical data involved visually interpreting Corona images to identify areas with visible canopy changes, such as clear-cuts and windthrow. For more recent data, forest cover loss was automatically extracted from Landsat and Sentinel-2 images using algorithms from the Global Land Analysis & Discovery platform and Google Earth Engine, respectively. This automated extraction ensured consistent and repeatable measures of forest disturbances over time.

2.4. Landscape Analysis

From the dataset resulting from combining the manually digitized forest cover loss from the Corona images, the automatically extracted forest cover loss from the Potapov and Hansen surveys, and the automatically extracted forest cover loss from the Sentinel 2 images, a raster was created using QGIS. To analyze and quantify changes in forest cover that produced landscape fragmentation, the raster was the input data to perform Forest Area Density Analysis (FAD) and Morphological Spatial Pattern Analysis (MSPA) in the Guidos Toolbox platform.

MSPA provides complex pathway information, branching, and user selectable internal features specific to the spatial model [24]. The input raster image is composed of the data area (pixels with information and designated to be in the foreground) and the missing area, pixels without information. MSPA renders much more morphometric detail of the foreground pixels, as well as the possibility of detecting holes along the foreground boundaries. The visual result is represented by 10 classes (Figure 2).

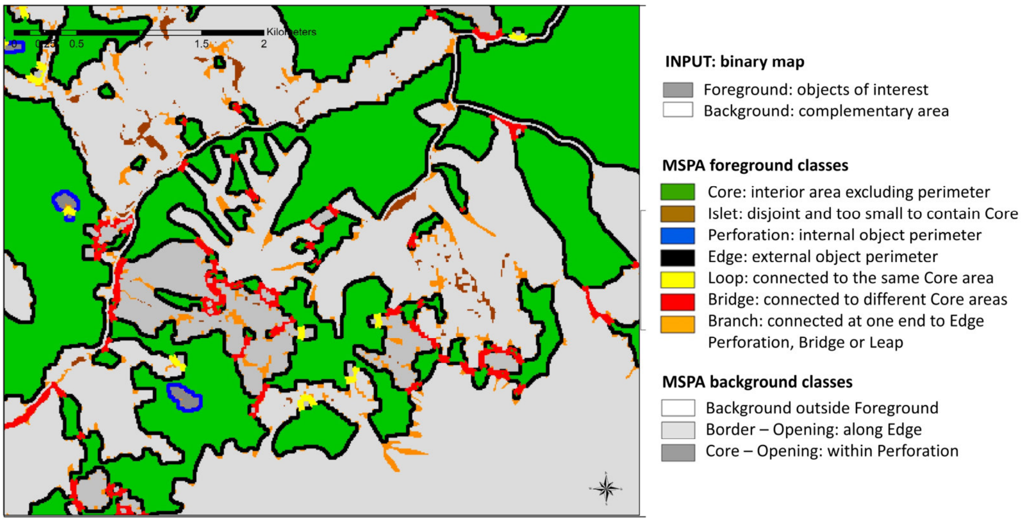


Fig. 2. *Overview of MSPA classes, map Oticu - Valea Colților -Luțele area*

The FAD analysis evaluates the proportion of foreground pixels relative to the total number of pixels in the neighborhood, using a per-pixel moving window evaluation scheme. The resulting map is color-coded by five colours in a range from 0 to 100% (Table 2) and allows us to easily compare fragmentation levels and changes over time [33].

Fragmentation classes Table 2

FAD – 5 Class	Range	Colour
Rare	FAD < 10%	
Patchy	10% < FAD < 40%	
Transitional	40% < FAD < 60%	
Dominant	60% < FAD < 90%	
Interior	90% < FAD < 100%	

2.5. Evaluating Human Interventions

To understand the impact of human interventions on forest structure and ecosystem services, we integrated the results from FAD and MSPA with historical and contemporary forest management practices. By comparing disturbances identified in historical (Corona) and contemporary (Landsat, Sentinel-2) data, we assessed changes in forest management practices and their impacts over time. Changes in forest connectivity and fragmentation were analyzed to understand their implications for ecosystem services, such as biodiversity conservation and climate regulation. Based on this comprehensive analysis, we developed recommendations for sustainable forest management practices that mitigate negative impacts and enhance positive outcomes for ecosystem services.

To conduct the analysis, we performed a paired t-test: To compare the mean FAD values between the two periods (1970-1990 and 1990-2020), to determine if there is a statistically significant difference between them. To analyze the distribution changes in MSPA classes between the two periods we performed the chi-square test to examine the distributions of categorical data in order to see if there are significant differences between the two periods.

3. Results

3.1. Disturbances Over Half a Century in Pecineagu Watershed Forests

Changes and losses of forest cover were identified in 142 ha of an estimated total area of 6,220 ha of forest cover analyzed. Of these, in 15% of the total area affected by disturbance a clear-cutting treatment was applied, in about 30% afforestation works preceded, by clear-cutting, and in 30% of the total area affected by disturbance the works applied are not known, as they were not recorded in the management plans (Table 3).

Table 3

Satellite and management plan observed harvests during the 1986 and 1996 management plans period

Analyzed parameter	Surface	
	ha	%
Unregistered	43.04	30.23
Planted	33.43	23.48
Planted in old plantations	6.18	4.34
Cleaning cuts	32.28	26.89
Clear-cuts	21.44	15.06
Grand total	142.37	100

The losses of forest cover not recorded in management plans amounted to 43.04 ha, of which about 88% are areas smaller than 2,500 m^2 (Figure 3a), and the rest could be considered satellite errors, tree crown errors, disturbances caused by natural processes of low intensity, not reported in the management plans. It was found that most of the areas affected by disturbances, not reported in the management plans, are below the average area (Figure 3b), with 12% having an area of more than 2,500 m^2. This is a situation encountered, for example, in unit 68 D of UP IV Tamas, where an area of 1.55 ha was affected by disturbances, which, however, due to an error, was not reported in the management plan.

The low intensity forest works (thinning, clearing) which were applied in various areas (e.g. unit 78 A in UP IV Tamas (Figure 4c) and units 68 A, 18 D, 18 E, 18 A in UP V Izvoarele Dambovitei (Figure 4d), in a total area of 65 ha, were recorded in the management plans but could not be identified from the satellite imagery (Figure 4a) and the data in the management plans were recorded at the forest plot level, so we could not know the affected area or the spatial location (Figure 4b).

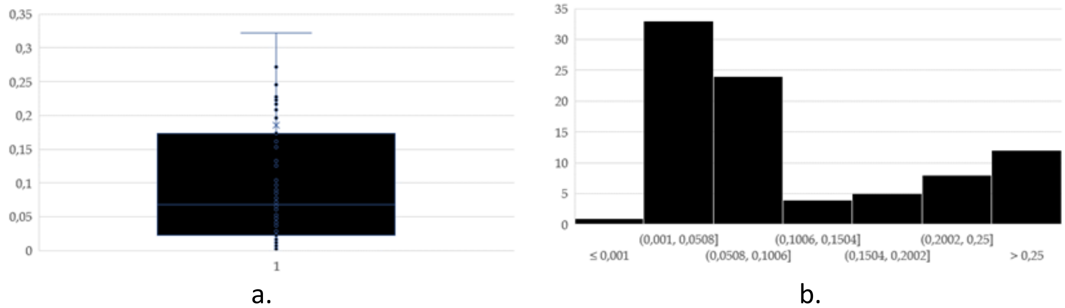


Fig. 3. *Area (ha) of unrecorded works in the management plans, but identified in satellite images (a.) and the distribution of unrecorded areas (ha) in management plans (b.)*

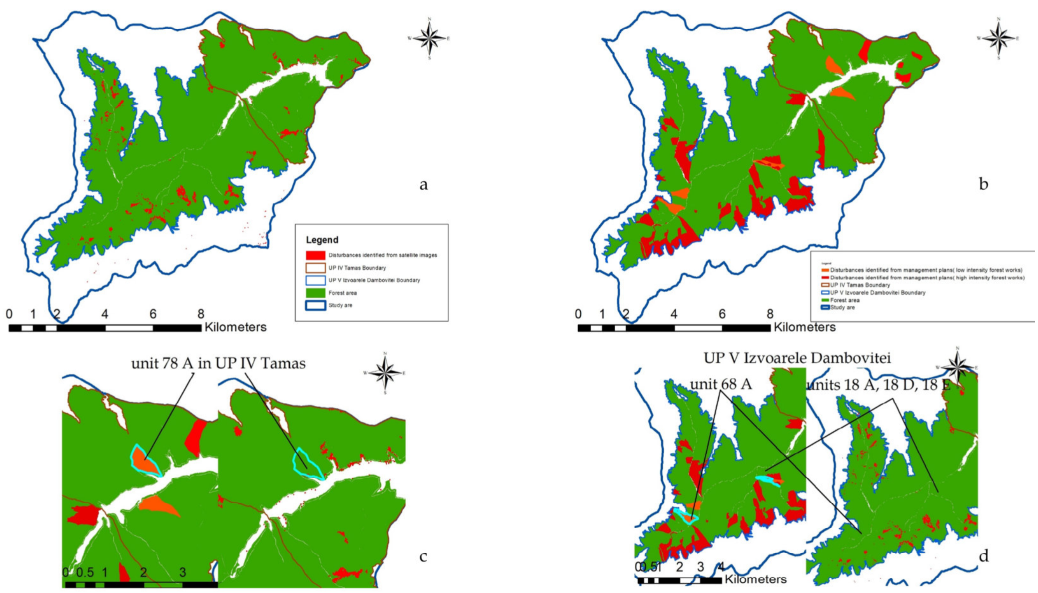
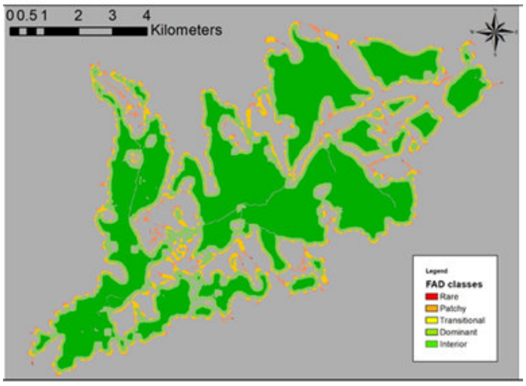


Fig. 4. *Disturbances identified: a. from satellite images; b: from management plans c: e.g. 78 A UP IV Tamas; d. e.g. 68 A, 18 D, 18 E, 18 A in UP V Izvoarele Dambovitei*

3.2. Comprehensive Landscape Analysis Using Forest Fragmentation Analysis

The FAD analysis for the periods 1970-1990 (Figure 5a) and 1990-2020 (Figure 5b) allowed quantification of forest fragmentation in the Pecineagu watershed and monitoring of changes in forest landscape fragmentation over time. The result of the comparative FAD analysis for the two periods shows no major changes, with an average FAD of 86% in the period 1970-1990 and 88% in the period 1990-2020 (Table 4). The inner layer and the dominant layer have the highest values in both situations.



a. b.

Fig. 5. *FAD analysis for the period: a. 1970-1990; b. 1990-2020*

Changes in FAD class layers (1970-2020) for Pecineagu watershed Table 4

FAD Classes	Colour	1970-1989 [%]	1990-2020 [%]
Rare		0.05	0.08
Patchy		2.81	1.86
Transitional		9.14	6.63
Dominant		26.57	24.50
Interior		61.42	66.93
FAV_AV		86.03	88.46

The result of the multi-scale FAD analysis indicates that an extremely low percentage of forest habitats (0.02%) fall into the rare layer class, while the best represented class is the dominant layer class (67.69% - Table 5). A clear differentiation between fragmentation classes is observed following the change in window size. The dominant layer occupies the highest percentage in scenario 4 and the inner layer in scenario 3. The synthesis value of 67.69% of the dominant layer indicates that the forest in the study area is characterized by high connectivity and low fragmentation.

Table 5

Summary of the observable scale for the analysis of fragmentation between 1970 and 2020

FAD: FragmClass/ObsScale	1	2	3	4	5	Summary
Rare	0.05	0.11	0.21	0.15	0.14	0.02
Patchy	1.51	2.88	5.60	13.75	25.45	3.13
Transitional	5.24	7.95	13.73	24.37	44.76	13.79
Dominant	15.76	24.63	33.87	47.44	29.65	67.69
Interior	8.06	14.30	21.55	13.68	0	15.38
Intact	69.38	50.13	25.04	0.61	0	0

3.3. Comprehensive Landscape Analysis Using Morphological Spatial Pattern Analyses (MSPA)

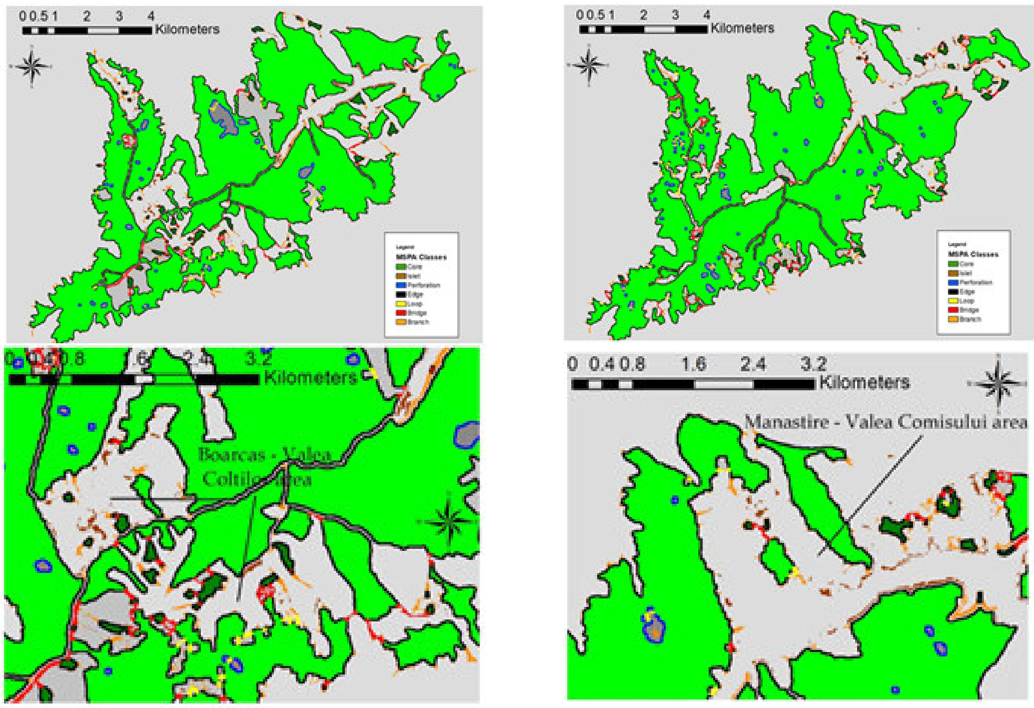
The MSPA method allowed the monitoring of changes in the spatial pattern of the landscape by comparing the data taken in the two time periods, i.e., 1970-1990 and 1990 - 2020. The observed changes were expressed in percentages of MSPA - class layers (Table 6). The results indicate that changes in forest cover over the two periods examined resulted in a 3% increase in area classified as core, a 28% increase in perforation layer, and a 64% increase in loop layer. A 35% decrease in the islet layer, a 12% decrease in the edge layer, a 16% decrease in the bridge layer, a 13% decrease in the branch layer, and a 43% decrease in the opening layer indicate that spatial isolation within the analyzed area has decreased.

Change in MSPA class layers (1970-2020) for Pecineagu watershed Table 6

MSPA Classes	Colour	1970-2020 [%]	1970-1990 [%]	1990-2020 [%]	MSPA Change [%]
Core		71.12	78.74	81.04	3
Islet		1.14	0.68	0.44	35
Perforation		1.41	1.05	1.34	28
Edge		21.12	15.90	14.04	12
Loop		0.38	0.14	0.23	64
Bridge		1.12	0.50	0.42	16
Branch		3.70	2.14	1.87	13
Opening		1.79	1.34	0.76	43

MSPA for Pecineagu watershed showed two areas affected by strong fragmentation, Boarcas-Valea Coltilor-Berevoiu area in the period 1970-1990 (Figure 6a) and Manastire-Valea Comisului area in the period 1990-2020 (Figure 6b).

In the Valea Coltilor (Figures 6a and 7b) area, most of the undisturbed areas are in the form of islands. The central area, on the other hand, is characterized by large areas of undisturbed forest. However, there are areas classified as perforation (internal objective perimeter), which is highlighted by large clear-cuts in the past. This spatial distribution of disturbance was captured in the MSPA analysis by 71.12% of forests classified as core in the period 1970-2020. However, 21.12% of the forests in the period 1970-2020 were classified as edge given the distribution of disturbances in the area Boarcas-Valea Coltilor-Berevoiu-Lutele (Figure 7b), Valea Vladului (Figure 7c), and in the area Manastire-Valea Comisului (Figure 7d).



a. b.

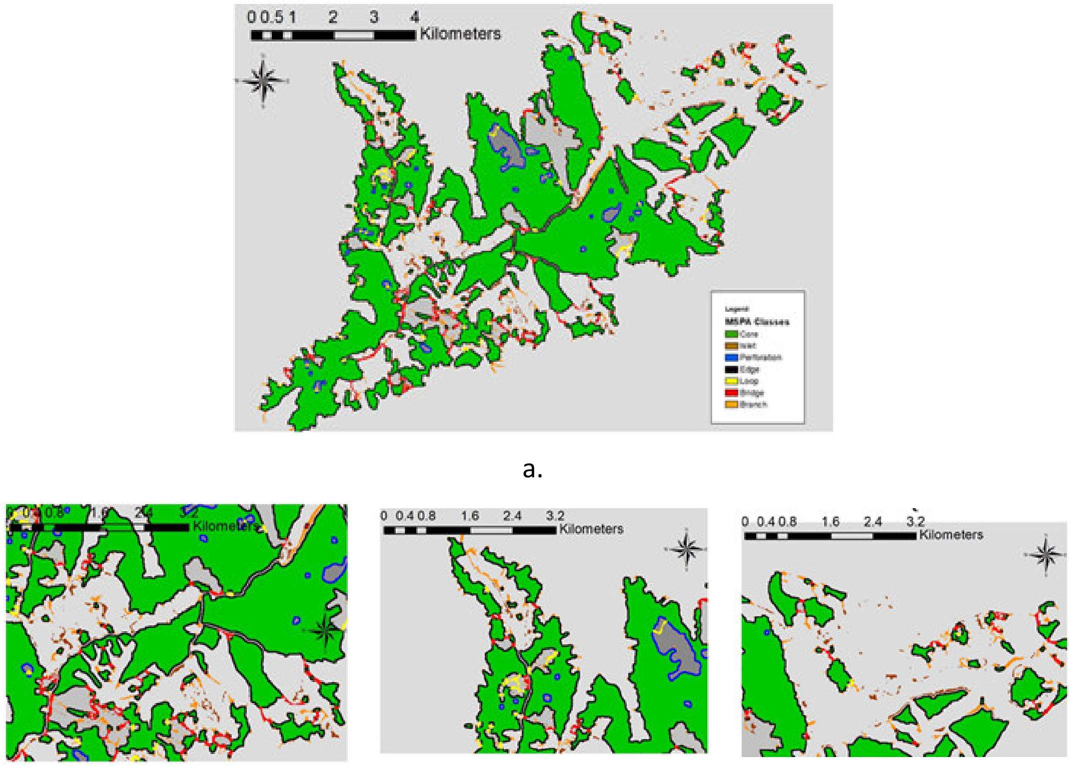
Fig. 6. *MSPA for the period: a. 1970-1990; b. 1990-2020*

3.4. Human Interventions Evaluation on Connectivity and Landscape

Statistical evaluation of human interventions on connectivity and landscape was conducted to assess differences across time periods. A paired t-test was performed to compare the mean Forest Area Density (FAD) values between 1970–1990 and 1990–2020. The analysis yielded a t-statistic of -0.33 and a p-value of 0.76. Since the p-value exceeds 0.05, the null hypothesis cannot be rejected, indicating no statistically significant difference in mean FAD values between the two periods.

Additionally, a chi-square test analyzed changes in the distribution of Morphological Spatial Pattern Analysis (MSPA) classes between the same periods. The results showed a chi-square statistic of 0.44 and a p-value of 0.9996. As the p-value is significantly greater than 0.05, the null hypothesis could not be rejected, suggesting no statistically significant changes in the distribution of MSPA classes.

The overall statistical analysis indicates no significant differences in mean FAD values or MSPA class distributions between the analyzed periods.



a.

b. c. d.

Fig. 7. *MSPA for the entire 1970-2020: a. Pecineagu watershed; b. area Boarcas - Valea Coltilor – Berevoiu – Lutele; c. area Valea Vladului; d. area Manastire - Valea Comisului*

4. Discussion

The capacity of forests to deliver essential ecosystem services depends significantly on their location, structure, and management practices [19]. This study highlights the critical role human interventions play in shaping forest continuity and ecosystem services in the Pecineagu watershed. Diverse forest management approaches, including clear-cutting and afforestation, were observed to have varying impacts, emphasizing the need for strategies that balance resource extraction with conservation goals, especially given the growing challenges posed by climate change [24].

The integration of satellite remote sensing technologies in this study has proven invaluable for monitoring forest dynamics. While remote sensing effectively identifies and quantifies disturbances, its limitations underscore the importance of combining these technologies with ground-based validation and emerging tools. Such an integrated approach can enhance the accuracy and reliability of forest management practices and environmental monitoring efforts.

One notable finding of this study is the discrepancy in disturbance records between forest management plans and satellite data. Approximately 30% of the disturbances were not documented in management plans, highlighting gaps in record-keeping and the need for accurate, comprehensive data. Smaller disturbances, particularly those under 2,500 m², were often omitted, potentially due to their perceived insignificance or errors in satellite imagery. Addressing these gaps is critical for effective forest management and the development of sustainable policies.

Landscape analysis revealed no significant changes in forest connectivity or fragmentation across the study periods. The Forest Area Density (FAD) analysis showed consistent high connectivity, with an average FAD of 86% for 1970–1990 and 88% for 1990–2020. Similarly, the Morphological Spatial Pattern Analysis (MSPA) identified two areas—Boarcas-Valea Colților-Berevoiu (1970–1990) and Mănăstire-Valea Comisului (1990–2020)—experiencing substantial fragmentation. These findings suggest that while overall fragmentation metrics remained stable, localized disturbances could significantly impact ecosystem services.

The sensitivity analysis of disturbance identification through satellite remote sensing highlights its potential to revolutionize forest monitoring. Long-term trends identified through FAD and MSPA analyses underscore the importance of continuous observation for adaptive management. These insights are crucial for maintaining forest health, productivity, and biodiversity.

This study also provides valuable insights into the sustainability of current forest management practices in Romania. It underscores the need for a more balanced approach that integrates historical context, contemporary data, and ecological considerations. Updating management plans with accurate satellite data and incorporating advanced technologies into monitoring practices are imperative steps toward sustainable forest resource utilization and conservation.

5. Conclusions

This study provides valuable insights into the long-term impacts of human interventions on forest structure and connectivity in the Pecineagu watershed. The findings reveal stable forest connectivity and low fragmentation over time, with localized areas experiencing significant disturbances. While overall fragmentation metrics remained largely unchanged, shifts in the spatial patterns of disturbances emphasize the evolving nature of forest management practices.

A critical discovery was the discrepancy between recorded disturbances in forest management plans and those detected via remote sensing, with approximately 30% of disturbances undocumented. This underscores the need for more accurate and comprehensive data recording to ensure sustainable forest management. The study also highlights the utility of remote sensing in monitoring forest dynamics, although its limitations suggest the importance of combining it with ground-based methods for improved accuracy.

The stable connectivity observed provides a foundation for sustainable management, but the variability in disturbance patterns calls for adaptive strategies tailored to specific local contexts. Continuous monitoring using advanced technologies, coupled with updated management practices, is essential to maintaining forest health and ecosystem services.

In conclusion, this research demonstrates the importance of integrating historical data with modern tools to understand and manage forest ecosystems effectively. The lessons from this study can guide more sustainable forest management practices, ensuring resilience in the face of environmental and anthropogenic challenges.

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