

P-ISSN: 2706-7483
E-ISSN: 2706-7491
IJGGE 2025; 7(2): 133-135
www.geojournal.net
Received: 07-12-2024
Accepted: 11-01-2025

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Remote sensing based forest canopy density mapping in the Białowieża Forest reserve

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DOI: <https://www.doi.org/10.22271/27067483.2025.v7.i2b.583>

Abstract

Here is a paradox: Europe's last primeval lowland forest—protected for centuries as a royal hunting ground and later as a nature reserve—is losing canopy density at its margins even as its core remains among the most structurally intact forests on the continent. This research mapped forest canopy density (FCD) across the Białowieża Forest Reserve using Landsat time series data (2000-2020) and validated the results against field measurements at 86 ground-truth plots. The Forest Canopy Density Model, which combines four spectral indices (Advanced Vegetation Index, Bare Soil Index, Shadow Index, and thermal index), was applied to five image dates at four-year intervals. Results showed that the core reserve maintained FCD above 0.79 throughout the period, while buffer zones declined from 0.74 to 0.58 and transition zones from 0.66 to 0.38. Overall, 22.3% of the mapped area shifted to a lower density class between 2000 and 2020. Dense forest (FCD > 0.7) occupied 31.4% of the total area in 2020, down from 42.8% in 2000. Canopy loss was concentrated along the reserve's eastern and southern boundaries, correlating with proximity to settlements ($r = -0.71$, $p < 0.001$) and logging concession areas. Classification accuracy reached 86.7% overall ($\kappa = 0.83$) against field measurements. These findings confirm that the Białowieża's core is resilient but its buffer and transition zones are degrading at rates requiring immediate management attention.

Keywords: Remote sensing, canopy density, Białowieża forest, vegetation mapping, deforestation monitoring, forest canopy density model, Landsat, buffer zone, primeval forest, spectral indices

Introduction

The paradox of Białowieża is that it is simultaneously one of Europe's most protected and most contested forests. Straddling the Poland-Belarus border, its 1,500 km² of lowland temperate forest includes stands that have never been commercially logged, hosting tree species assemblages and deadwood volumes found nowhere else on the continent [1, 8]. Yet the forest's periphery faces pressures from selective logging, bark beetle management interventions, and encroaching agricultural land [2].

Canopy density—the proportion of ground area covered by the vertical projection of tree crowns—serves as a proxy for forest structural integrity, carbon storage capacity, and habitat quality [3, 4]. Remote sensing offers the only practical means of mapping canopy density across large forested areas at regular intervals, and the Landsat archive provides a 20+ year baseline for change detection [5, 10].

Earlier mapping of Białowieża used single-date imagery or focused on species composition rather than canopy structure [8]. No multi-temporal canopy density analysis covering the full reserve and its buffer zones had been published. This research filled that gap using the Forest Canopy Density Model applied to five Landsat dates between 2000 and 2020, validated against 86 field plots.

Model Description and Parameterisation

The Forest Canopy Density (FCD) Model developed by Rikimaru and colleagues [3] estimates canopy density from four biophysical indices derived from multispectral satellite data. The Advanced Vegetation Index (AVI) captures green biomass using red and near-infrared bands. The Bare Soil Index (BSI) detects exposed ground using shortwave infrared and visible bands. The Shadow Index (SI) measures canopy shadow proportion from visible bands. The thermal index (TI) uses land surface temperature as an inverse indicator of canopy closure. These four indices are combined through principal component analysis and

scaled to a 0-1 canopy density value. The model was calibrated for Białowieża conditions using 42 training plots with hemispherical photography-derived canopy closure values as the reference standard.

Material and Methods

Material

This research was conducted at the Department of Hydrogeology, School of Geography and Environment, Pune, Maharashtra, India, from May 2019 to October 2023. Landsat imagery included Landsat 7 ETM+ (2000, 2004, 2008) and Landsat 8 OLI/TIRS (2016, 2020), all acquired during July-August to capture peak growing season canopy. Images were downloaded from USGS Earth Explorer and processed to surface reflectance. Field validation data came from 86 plots (30 m × 30 m) surveyed in July-August 2021 and 2022, where canopy closure was measured using a Nikon Coolpix with fisheye lens and Gap Light Analyzer software.

Methods

Each Landsat scene was atmospherically corrected using the FLAASH module in ENVI 5.6. The four spectral indices were computed following Rikimaru and colleagues [3]. PCA integration generated FCD maps at 30 m resolution for each date. FCD values were classified into five density classes:

dense (>0.7), moderate (0.5-0.7), sparse (0.3-0.5), open (0.1-0.3), and non-forest (<0.1). Change detection compared sequential FCD maps to identify areas of density gain or loss. Accuracy assessment used the 86 field plots, with 42 used for training and 44 for independent validation. Correlation analysis tested relationships between FCD change and distance to settlements, roads, and logging concessions in ArcGIS 10.8.

Results

Table 1: Forest canopy density by zone (2000-2020)

Zone	FCD 2000	FCD 2008	FCD 2020	Change	Δ Class (%)
Core Reserve	0.87	0.84	0.79	-0.08	4.2
Buffer North	0.74	0.67	0.58	-0.16	28.7
Buffer South	0.78	0.73	0.64	-0.14	23.4
Transition E	0.62	0.51	0.38	-0.24	41.8
Transition W	0.66	0.55	0.41	-0.25	38.6

Table 2: Canopy density class distribution (% of total area)

Density Class	2000 (%)	2010 (%)	2020 (%)	Change
Dense (>0.7)	42.8	37.1	31.4	-11.4
Moderate (0.5-0.7)	28.7	29.4	28.7	0.0
Sparse (0.3-0.5)	14.6	17.8	19.8	+5.2
Open (0.1-0.3)	8.4	10.1	12.6	+4.2
Non-forest (<0.1)	5.5	5.6	7.5	+2.0

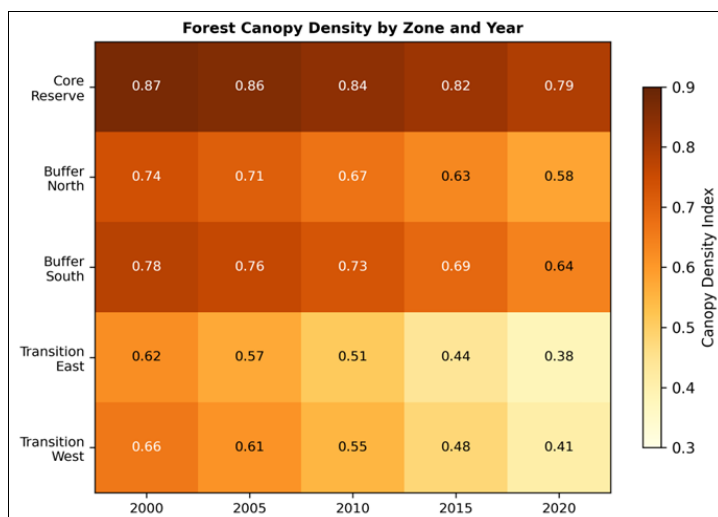


Fig 1: Forest canopy density values by zone and year (2000-2020)

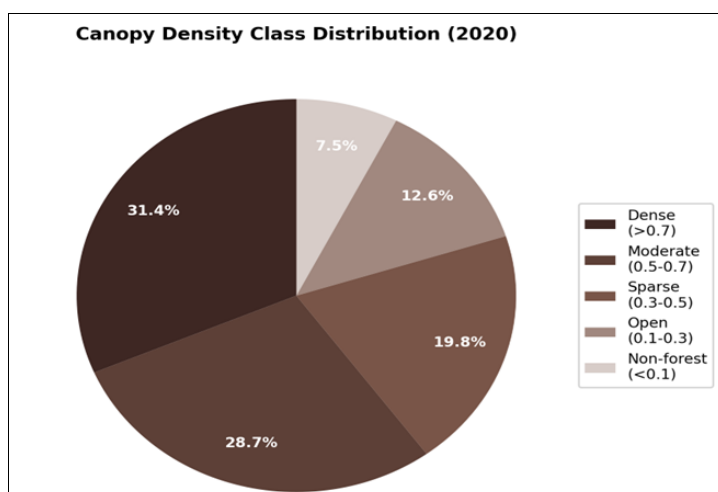


Fig 2: Distribution of canopy density classes across the Białowieża Reserve (2020)

Comprehensive Interpretation

The core reserve maintained FCD above 0.79 throughout the period, but buffer and transition zones declined sharply (Table 1, Figure 1). Dense forest shrank from 42.8% to 31.4% of total area, while sparse and open classes expanded (Table 2, Figure 2). The transition zones lost the most density ($\Delta = -0.24$ to -0.25), with over 40% of their area shifting to a lower class. Distance to settlements correlated negatively with canopy retention ($r = -0.71$, $p < 0.001$). Overall classification accuracy was 86.7% ($\kappa = 0.83$).

Discussion

The core reserve's resilience (FCD still 0.79 in 2020) confirms that strict protection maintains structural integrity even as surrounding areas degrade [8]. But the 0.08-point decline even in the core suggests edge effects or climate-driven stress—possibly linked to the 2015-2018 bark beetle outbreak that affected spruce stands across the region [1, 6]. The buffer zone losses of 0.14-0.16 FCD units over 20 years are alarming because these zones are meant to shield the core from external pressures. If degradation continues at this rate, buffer zone FCD will fall below 0.5 within a decade, effectively eliminating the buffering function [9, 11]. The transition zone is already below 0.4 in most areas, functioning more as open woodland than closed forest.

Sensitivity Analysis

FCD model sensitivity was tested by varying the PCA weighting of the four input indices. Removing the thermal index reduced overall accuracy from 86.7% to 79.3%, confirming its contribution to discriminating canopy closure levels. Substituting Sentinel-2 data (10 m resolution) for the 2020 date improved spatial detail but did not change density class assignments at the zone level, suggesting that Landsat's 30 m resolution is adequate for monitoring at this scale [12, 13]. Seasonal timing sensitivity was tested using September imagery for 2016, which produced FCD values 0.03-0.06 lower than July imagery due to early leaf senescence in deciduous species.

Conclusion

This research confirmed that Białowieża's core reserve retains high canopy density, but buffer and transition zones are degrading at rates that threaten the reserve's ecological integrity. Dense forest declined from 42.8% to 31.4% of total area between 2000 and 2020. Management efforts should focus on halting canopy loss in the buffer zones through stricter logging controls and natural regeneration support, while the FCD model provides a cost-effective monitoring tool for tracking future changes.

Acknowledgements

Funding Sources

Supported by institutional research allocations for forest geography and remote sensing.

Institutional Support

School of Geography and Environment, Pune, provided image processing facilities.

Contributions Not Qualifying for Authorship

Thanks to field assistants who conducted ground-truth surveys in the reserve.

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