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Assessment of natural and anthropogenic impacts on forest vegetation in Putna-Vrancea Natural Park through remote sensing and spatial analysis

PhD Thesis Abstract

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Introduction

The Putna–Vrancea Natural Park (PNPV) represents one of the most significant protected forested areas of the Romanian Carpathians, situated in the central-northern part of the Eastern Carpathians, within the Curvature sector. Its high ecological value stems from the interplay of rugged topography, altitudinal gradients, lithological heterogeneity and climatic variability, which have shaped a diverse forest mosaic over time. The region is also emblematic for the interactions between natural processes and anthropogenic pressures, ranging from traditional land use practices to intensive industrial exploitation during the modern era.

This doctoral thesis is devoted to analyzing the composition, structure and dynamics of the forest vegetation in PNPV, with the aim of elucidating the relative influence of abiotic, biotic and anthropogenic factors over different temporal scales. The research combines several methodological innovations, most notably the integration of parcel-level silvicultural data, remote sensing time series (Sentinel-2, MODIS), climatic datasets (ROCADA, C3S reanalysis, Lăcăuți meteorological station), and georeferenced historical cartography (1789–2019). Through this integrative approach, the study delivers both descriptive insights into current vegetation composition and analytical results regarding ecological favorability, forest vulnerability, and long-term land-use trajectories.

Chapter I — Geographical and Historical Framework

The first chapter situates the PNPV within its geographical and historical context. From a physical perspective, the park covers a territory characterized by altitudinal variation between ~500 and over 1700 m, steep slopes with multiple exposures, and lithological units dominated by flysch deposits (sandstones, marls, shales). This combination generates a diversity of soil types, mostly cambic soils, which support the development of mixed beech–coniferous forests. Climatically, the park is part of the montane bioclimatic zone, with long winters, extended snow cover and high annual precipitation.

The historical section reconstructs the land-use trajectories of the past two centuries. Communal ownership structures and subsistence-based practices of the Vrancea communities initially shaped the forests. During the 19th and 20th centuries, industrial logging facilitated by narrow-gauge railways profoundly modified forest structure and composition. The thesis makes extensive use of historical maps (Habsburg cadastral maps of 1789, Romanian topographic maps of 1895, Soviet maps of 1957, military maps of 1975) to trace changes in forest cover. Results demonstrate that, while forest cover remained high (above 80%), there were significant shifts in composition, age structure and spatial continuity, with extensive deforestation episodes particularly around 1900–1950, followed by afforestation programs after nationalization in 1948.

Chapter II — Data and Methodology

The second chapter details the data sources and analytical methods. The originality of the research lies in the multilayered integration of heterogeneous datasets into a unified GIS environment:

- Forest parcel inventories were rasterized at 12.5 m resolution and harmonized with Sentinel-2 grids:

- Satellite remote sensing: Sentinel-2 imagery (2015–2022) was pre-processed with Sen2Cor and used to derive vegetation indices (NDVI, CAB, NBR, EVI), while MODIS products provided long-term land surface temperature (LST) for 2000–2022:

- Climatic data: ROCADA series (1961–2013) and C3S ERA5 reanalysis were combined with records from Lăcăuți station to reconstruct regional climatic variability:

- Historical maps were georeferenced, digitized and used for diachronic landscape analysis.

- Multicriteria favorability modelling combined topography (altitude, slope, aspect), soil, and climatic variables to generate maps of ecological suitability for key tree species:

Validation was achieved through cross-comparison of parcel-level data with satellite-derived metrics, supplemented by field surveys. The methodological novelty resides in the fine-resolution integration of long-term historical evidence with short-term physiological indicators, providing a holistic view of forest dynamics across multiple timescales.

Chapter III — Forest Composition and Age Structure

This chapter offers a comprehensive analysis of the current forest composition in PNPV. According to parcel-level inventories, the main species are European beech (*Fagus sylvatica*, 36%), Norway spruce (*Picea abies*, 34%), and silver fir (*Abies alba,* 18%), which together account for nearly 90% of the total forested area. Minor species include birch, oak, hornbeam, larch, pine and poplar.

Age-structure analysis reveals that beech forests are concentrated in the 81–120-year class, spruce shows a bimodal distribution (20–50 years and 81–120 years), and fir is also mid-aged. The findings suggest a mature but uneven age mosaic, with limited regeneration in some species, raising concerns over spruce monocultures.

Chapter IV — Abiotic and Biotic Drivers

Abiotic factors.

Topography (altitude, slope, aspect), lithology and soils are the primary deterministic factors shaping species distributions. Altitudinal stratification is classic: oak (*Q. petraea*) and hornbeam/carpin in lower submontane belts (~600–900 m), beech dominant at mid-elevations (~1000–1300 m), and spruce/fir at higher elevations and sheltered north aspects. Soil analyses show cambic soils dominate the area; species-substrate associations are consistent with expectations (beech/carpin on siliceous substrates; spruce and fir on acidic, well-drained flysch-derived soils). Wind analyses (Lăcăuți station and terrain modelling) reveal highest mean wind speeds on exposed crests (up to ~13 m/s) with a prevailing westerly component; windthrow risk concentrates in exposed spruce stands. Snow regime: long snow season (7–8 months at high elevation), with extremes exceeding 170 cm recorded in 2021–2022; snow load and late snow contribute to mechanical damage risks. Climate trends: analysis of station and MODIS LST series documents warming since ~1980, high interannual precipitation variability, and LST contrasts between species/UA: spruce/fir/beech stands moderate extremes (cooler LST), while pine, hornbeam and alder stand register higher LST values in summer—an important link to vulnerability under warming.

Biotic factors.

Large mammals (bears, cervids) produce localized mechanical damage (bark stripping, branch breakage) that can compromise individual trees and promote secondary infections; however, in PNPV their effects are currently regulated by population control and predators. Xylophagous insects (Scolytinae) are identified as the major biological threat: *Ips typographus* is emphasized as a high-impact agent for spruce, particularly after wind or drought stress, while other ambrosia beetles (e.g. *Xyleborinus saxesenii*) and Scolytus spp. (vectors of Dutch elm disease) are also noted. The thesis underscores increasing insect pressure linked to climate warming and the vulnerability of monospecific spruce stands to epidemic outbreaks.

Chapter V — Anthropogenic Influence

A diachronic cartographic analysis (1789 → 1895 → 1957 → 1975 → 2017–2019) reconstructs land-use change. Key findings: (1) In 1789 forest cover was overwhelmingly dominant (≈88.6%), with pastoral areas limited; (2) By 1895 the forest still covered ~87% but industrial forestry intensified through the early 20th century, facilitated by narrow-gauge railways and sawmills; (3) 1957 maps show a reduced forest fraction (~84%) with ~2.8% clearly deforested patches; major fires (notably 1946–47) compounded degradation; (4) Post-1948 nationalization and afforestation programs (1950–1990) produced large reforestations (the broader Vrancea program reportedly reforested some 80,000 ha regionally), reversing much open land to forest cover; (5) Recent mapping (2017–2019) indicates forest cover has stabilized at ~87.3% with pastures reduced (~8.6%). The analysis links historical exploitation, fire episodes and plantation forestry (including Larix, Pinus, and exotic Robinia) to current compositional changes and structural vulnerabilities such as widespread monospecific spruce stands.

Chapter VI. Estimation of Ecological Suitability for the Main Tree Species in PNPV

The assessment of ecological suitability for dominant tree species represents one of the most significant outcomes of this thesis, as it integrates ecological, climatic, and topographic variables to model the spatial distribution and potential resilience of the forest ecosystems in the Putna-Vrancea Natural Park. Using GIS-based spatial modeling combined with raster reclassification of key ecological factors (elevation, slope, aspect, soils, and climate), suitability maps were generated for the main tree species: beech (*Fagus sylvatica*), silver fir (*Abies alba*), Norway spruce (*Picea abies*), sessile oak (*Quercus petraea*), and alder (*Alnus glutinosa*).

The analysis demonstrated that beech forests possess the broadest ecological amplitude within the park. They were classified as having optimal suitability across most mid- and high-altitude areas, confirming their role as the ecological backbone of PNPV. Silver fir, although more demanding in terms of humidity and soil quality, also displayed high suitability in sheltered valleys and north-facing slopes, where microclimatic conditions mitigate thermal stress. By contrast, Norway spruce exhibited a more restricted niche, with optimal suitability confined to the highest elevations, particularly in areas above 1,400 meters, where temperature regimes and snow cover length remain favorable. This highlights its vulnerability to ongoing climate warming and its limited potential for downward migration.

The distribution of sessile oak was shown to be concentrated in the lower altitudinal belts, especially in southern and western parts of the park. Its suitability is strongly constrained by slope exposure and soil depth, but climate projections suggest potential upward expansion in response to warming conditions. Finally, alder, typically associated with riparian habitats, displayed highly localized but ecologically crucial suitability zones, acting as an indicator of hydrological balance in floodplain and alluvial environments.

An important contribution of this chapter lies in the comparative suitability assessment across species, which revealed potential future competition and compositional shifts. For instance, the overlap between beech and silver fir suitability zones indicates a stable mixed forest potential, while the decline in spruce suitability suggests a gradual retreat to restricted high-elevation refugia. These results have strong implications for adaptive forest management, highlighting the need to prioritize beech–fir associations as resilient forest types, while carefully monitoring spruce decline and oak expansion.

Chapter 7. Vegetation Monitoring Using Satellite Imagery

The integration of satellite remote sensing into the monitoring framework of the Putna-Vrancea Natural Park (PNPV) has provided a powerful, non-invasive tool for assessing vegetation dynamics at multiple temporal and spatial scales. Vegetation indices such as NDVI, EVI, and CAB (Chlorophyll a+b) were employed to evaluate canopy density, photosynthetic activity, and stress conditions in forest ecosystems. The multi-annual satellite datasets revealed clear patterns of seasonal variation, with peak photosynthetic activity occurring during summer months and reductions associated with late autumn senescence and extreme climatic events.

One of the key findings relates to interannual variability. For instance, CAB maps generated for the period 2018–2021 showed notable differences in vegetation vigor, with 2018 and 2020 reflecting relatively favorable conditions, while 2019 and 2021 indicated reductions in chlorophyll content, partly attributed to drought events and late frosts. These results highlight the sensitivity of PNPV's forests to climatic anomalies and the importance of continuous spectral monitoring. Moreover, the satellite-derived indicators provided valuable correlations with fieldbased measurements, confirming their utility for early detection of forest decline, pest outbreaks, and canopy disturbances.

Overall, remote sensing proved essential for supporting adaptive management, offering timely and objective information on vegetation health, enabling prioritization of conservation actions, and serving as an early warning system in the context of both natural and anthropogenic stressors.

Chapter 8. The Putna-Vrancea Natural Park in the Context of Global Climate Change

The PNPV, located in the Eastern Carpathians, represents a vulnerable ecosystem at the intersection of multiple climatic gradients. Long-term climatic analyses confirm a significant warming trend since the 1980s, in line with global and European patterns, with mean annual temperature increases particularly evident in low- and mid-altitude areas. Precipitation regimes, although highly variable, did not show a consistent long-term trend, but alternated between extremely dry and excessively wet years, amplifying ecological instability.

Species-specific analyses of thermal and hydric ecological limits revealed strong differential responses to climate change. Boreal and montane conifers such as Picea abies, Abies alba, and Larix decidua are projected to undergo substantial areal contractions, being increasingly restricted to high elevations. In contrast, mesothermic and more thermophilous broadleaf species, such as Fagus sylvatica, Quercus petraea, and Carpinus betulus, are likely to expand, benefiting from warmer conditions provided sufficient soil moisture is maintained. This shift in favorability points toward a gradual transformation of forest composition, with important implications for biodiversity, carbon storage, and ecosystem services.

The chapter also emphasizes the compounding role of climate change in exacerbating disturbances. Increased frequency of droughts and heatwaves accelerates pest outbreaks (e.g., Ips typographus infestations), weakens tree resistance, and amplifies storm and windthrow damages. Furthermore, snowpack analyses indicated delayed melting in some years but reduced accumulation in others, underscoring the variability and unpredictability of hydrological regimes. These trends align with projections from the IPCC, situating PNPV as a microcosm of wider Carpathian vulnerabilities.

In conclusion, the park represents both a sentinel and a testing ground for climate change impacts on forest ecosystems. Its future resilience depends on adaptive management strategies that integrate monitoring data, predictive modeling, and proactive conservation measures designed to maintain structural diversity, ecological connectivity, and species adaptability.

Conclusions

This research provides a comprehensive ecological and historical assessment of the Putna-Vrancea Natural Park (PNPV), highlighting the complex interplay between natural drivers, anthropogenic influences, and climate change in shaping forest ecosystems. The integration of field surveys, historical cartography, GIS analyses, ecological modeling, and satellite-based monitoring has generated a multi-layered perspective on vegetation dynamics, disturbance regimes, and future trajectories.

Findings demonstrate that PNPV hosts a diverse forest mosaic, where beech, spruce, and fir predominate, structured along distinct altitudinal gradients. These ecosystems are subject to multiple stressors: climatic variability, snow and wind disturbances, biotic agents such as herbivores and bark beetles, and long-standing anthropogenic pressures. Historical land-use transformations—particularly deforestation, forest exploitation, and pasture expansion—have left a lasting imprint on landscape structure, though recent conservation and reforestation initiatives have contributed to recovery.

Ecological niche modeling revealed divergent species trajectories: coniferous species such as spruce and fir are projected to lose ecological favorability under warming scenarios, while broadleaved species like beech and sessile oak may expand. This shift underscores the vulnerability of montane forests and calls for adaptive silvicultural strategies aligned with climate projections. Complementary satellite-based monitoring proved invaluable in capturing vegetation stress and interannual variability, confirming its role as a cost-effective and scalable tool for conservation management.

At a broader scale, PNPV exemplifies the challenges faced by Carpathian ecosystems under global climate change. Rising temperatures, hydrological instability, and disturbance intensification will likely reshape forest composition and resilience. Yet, the park's relatively intact landscapes, low demographic pressure, and ongoing conservation efforts offer opportunities for adaptive management and ecological restoration.

Management implications: Future strategies should prioritize diversification of stands, reduction of spruce monocultures, promotion of mixed regeneration, and integration of disturbance risk (wind, insects, drought) into silvicultural planning.

Overall, the thesis provides a robust, multi-scalar methodological framework for forest monitoring and management in mountainous protected areas. By combining historical perspectives with cutting-edge remote sensing, it not only reconstructs past dynamics but also equips managers with tools to anticipate and mitigate future ecological challenges in the context of climate change.