

Multi-temporal geospatial assessment of vegetation change patterns in the Natura 2000 site Bârnova Forest, integrating remote sensing and GIS analysis

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Abstract: This research presents an in-depth analysis of vegetation dynamics within a protected forest ecosystem, employing advanced remote sensing and GIS methodologies. The study utilizes Sentinel-2 satellite imagery, covering an eight-year period (2017 - 2024), to calculate and interpret key vegetation indices such as NDVI, allowing for a detailed assessment of both seasonal and long-term changes in vegetation health. By integrating high-resolution remote sensing data with local GIS layers, including species distribution, topography, and land use, the research explores the relationships between vegetation indices and environmental factors. Meteorological variables, such as precipitation, temperature, and solar radiation, are also analyzed using data from the ERA5 Land dataset to provide further context for vegetation dynamics. Through the use of spatial analysis and cluster methods, the study identifies correlations between vegetation patterns and variables such as terrain and species composition. Patterns observed in vegetation indices reflect the influence of factors such as slope, elevation, and species composition. The study provides a spatial overview of how these variables interact across the forest landscape, allowing for a more structured interpretation of vegetation change.

1. Introduction

The sustainable management of forest ecosystems represents one of the main challenges in biodiversity conservation within the context of environmental changes and the intensification of human activities (Fischer et al., 2010). Protected natural areas, such as Natura 2000 sites, are vital for maintaining ecological integrity and ensuring ecosystem services. The study of these areas is essential to understanding how different

tree species respond to climatic and topographic conditions, as well as the impact of human activities on biodiversity and natural habitats (Lindenmayer & Franklin, 2002).

The analysis of NDVI (Normalized Difference Vegetation Index), calculated from Sentinel-2 satellite imagery, enables the assessment of vegetation density and ecosystem health. In this study, NDVI values were correlated with climatic variables, such as temperature and solar radiation, as well as topographic characteristics, such as slope and aspect, to identify change trends and the factors influencing vegetation (Pettorelli et al., 2005).

Our study also includes a bibliometric analysis based on scientific publications indexed in Scopus, highlighting research trends in this field during the 1990–2024 period and providing a general scientific context for the use of remote sensing and GIS in studying forested areas. The analysis was conducted using a dataset extracted from the Scopus database and performed with the Bibliometrix software, which enables the exploration of global trends in a specific field of study (Aria & Cuccurullo, 2017).

This preliminary stage provides an in-depth analysis of the volume and geographical distribution of research, as well as key topics in the specialized literature, helping to understand the global context of studies and identify priority directions in the use of remote sensing and GIS (Donthu et al., 2021). The bibliometric analysis results reveal both a significant increase in scientific interest in this field and the major contributions of countries leading the research, such as the USA, China, and India, alongside international collaboration networks. This review thus offers a solid foundation for positioning the current research within existing global trends and contexts.

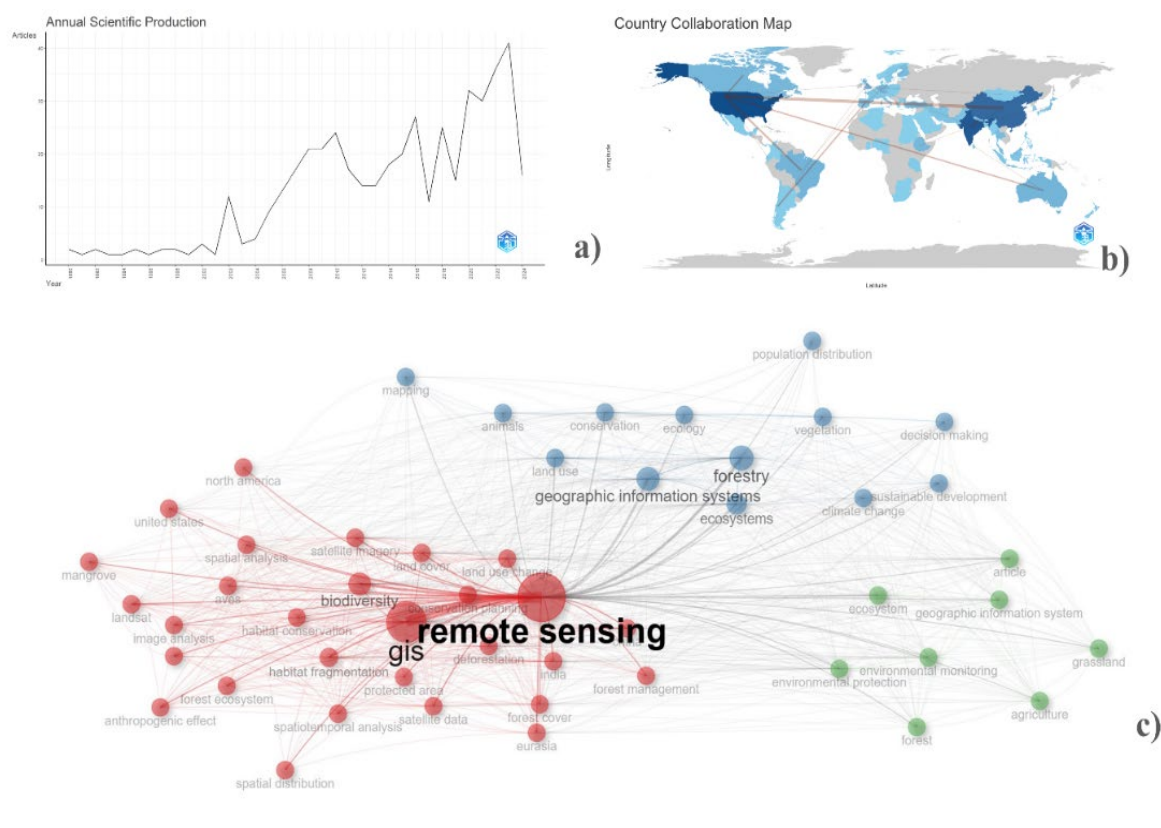


Figure 1 (a) The evolution of scientific articles published between 1990 and 2024, b) the distribution of international collaborations, c) the thematic network of keywords in the field

An important first aspect is the evolution of the number of publications between 1990 and 2024, illustrated in Figure 1a. The steady increase in the number of articles

reflects growing scientific interest in applying remote sensing and GIS technologies to environmental studies. From a relatively small number of publications in the 1990s, there is a sharp rise starting in the 2010s, coinciding with improved access to satellite imagery and the development of software tools for spatial data analysis. In Figure 1b, the map of international collaborations highlights the partnerships between countries driving advancements in this field. The USA holds a central position, with strong connections to countries such as China, Canada, Brazil, and Australia. These partnerships reflect the exchange of knowledge and resources among leading research centers. At the same time, collaborations between European countries and nations in South America are also evident.

Another relevant element is presented in Figure 1c, which shows the co-occurrence network of keywords used in articles within this field. The terms remote sensing and biodiversity occupy central positions in the network, being connected to concepts such as habitat fragmentation, forest management, clustering, and GIS. This highlights the broad applicability of remote sensing and GIS technologies in ecosystem monitoring and management. The importance of these central terms emphasizes that studying biodiversity and habitat fragmentation are priority research topics, with GIS serving as a key tool for modelling, analysing and monitoring forest landscape dynamics (Abad-Segura et al., 2020; Istrate et al., 2023).

2. Materials and methods

2.1 Study area

The study was conducted in the Bârnova Forest, located in the southeastern part of Iași County, north-eastern Romania, within the Central Moldavian Plateau, a subdivision of the Moldavian Plateau characterized by hilly terrain and extensive forest cover (Băcăuanu, 1968; Ungureanu, 1993). In the present study, the term Bârnova Forest refers to the entire forest area included within the Natura 2000 sites ROSPA0092 Bârnova Forest and ROSAC0135 Bârnova–Repedea, including the sectors where the two protected sites overlap. The analysed area covers 14,852.72 ha, representing one of the largest continuous forest ecosystems in the central-eastern part of the Moldavian Plateau.

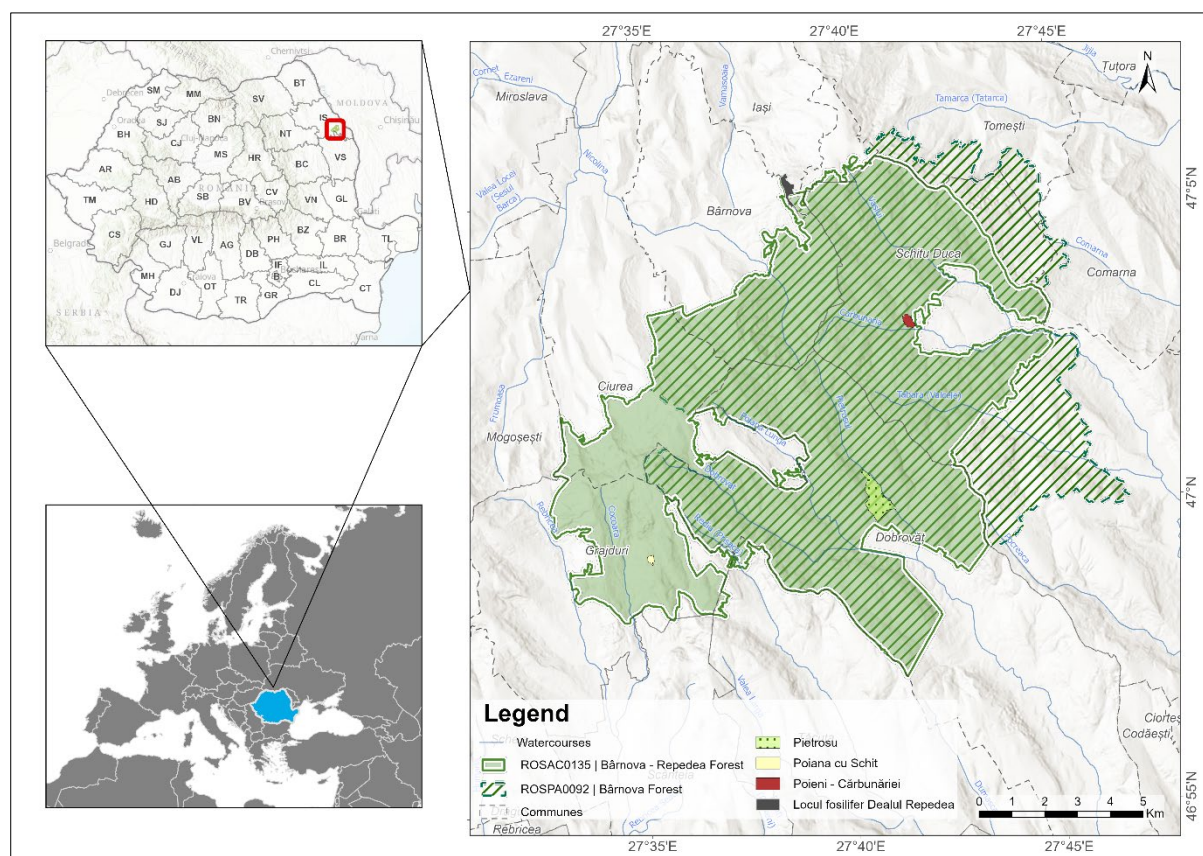


Figure 2 Location of the study area

Administratively, the study area extends across the communes of Bârnova, Ciurea, Comarna, Dobrovăț, Grajduri, Schitu Duca and Tomești and is crossed by the DN24 national road connecting Iași and Vaslui. The state-owned forest is managed by the National Forest Administration – Romsilva through the Iași Forest Directorate and is administered by the Dobrovăț, Lunca Cetățuii and Pădureni Forest Districts. The forest management plans prepared for these districts provided the forest stand database used in this study, including stand boundaries and the dominant tree species assigned to each forest stand.

Geologically, the area belongs to the Moldavian Platform and is developed on Mesozoic and Eocene sedimentary formations. The parent material, consisting of conglomerates, sandstones, clays and loess deposits, has favoured the development of medium- to high-quality soils. Elevation ranges from 103 to 419 m, with the landscape dominated by cuestas, steep slopes and structural plateaus shaped by differential erosion processes (Posea et al., 2005; Florea et al., 2003).

The climate is temperate-continental, typical of the Moldavian Plateau, with annual precipitation ranging between 450 and 650 mm. Summers are generally warm and relatively dry, whereas winters are cold and frequently accompanied by blizzards. The forest is traversed by several streams, including Valea Tinoasă, Nicolina and Dobrovăț, tributaries of the Bahlui River. Cambic chernozems and luvisols represent the dominant soil types, their distribution being closely related to the geological substrate (Bogdan et al., 2008).

The study area forms part of the European Natura 2000 ecological network through two protected sites: ROSPA0092 Bârnova Forest, designated as a Special Protection Area (SPA) under the Birds Directive for the conservation of migratory and

resident bird species, and ROSAC0135 Bârnova–Repedea, designated as a Special Area of Conservation (SAC) under the Habitats Directive for the protection of habitats and species of Community interest. ROSAC0135, formerly designated as the Site of Community Importance (SCI) ROSCI0135, was officially established as a SAC through Government Decision No. 685/2022 (Just.ro, 2022). The study area also includes four nationally designated nature reserves: Dealul Repedea Fossil Site (5.8 ha), a geological and palaeontological reserve, Poiana cu Schit (9.5 ha), a floristic reserve, and the Pietrosu (83 ha) and Poieni–Cărbunăriei (9.2 ha) forest reserves (Sincron, 2015).

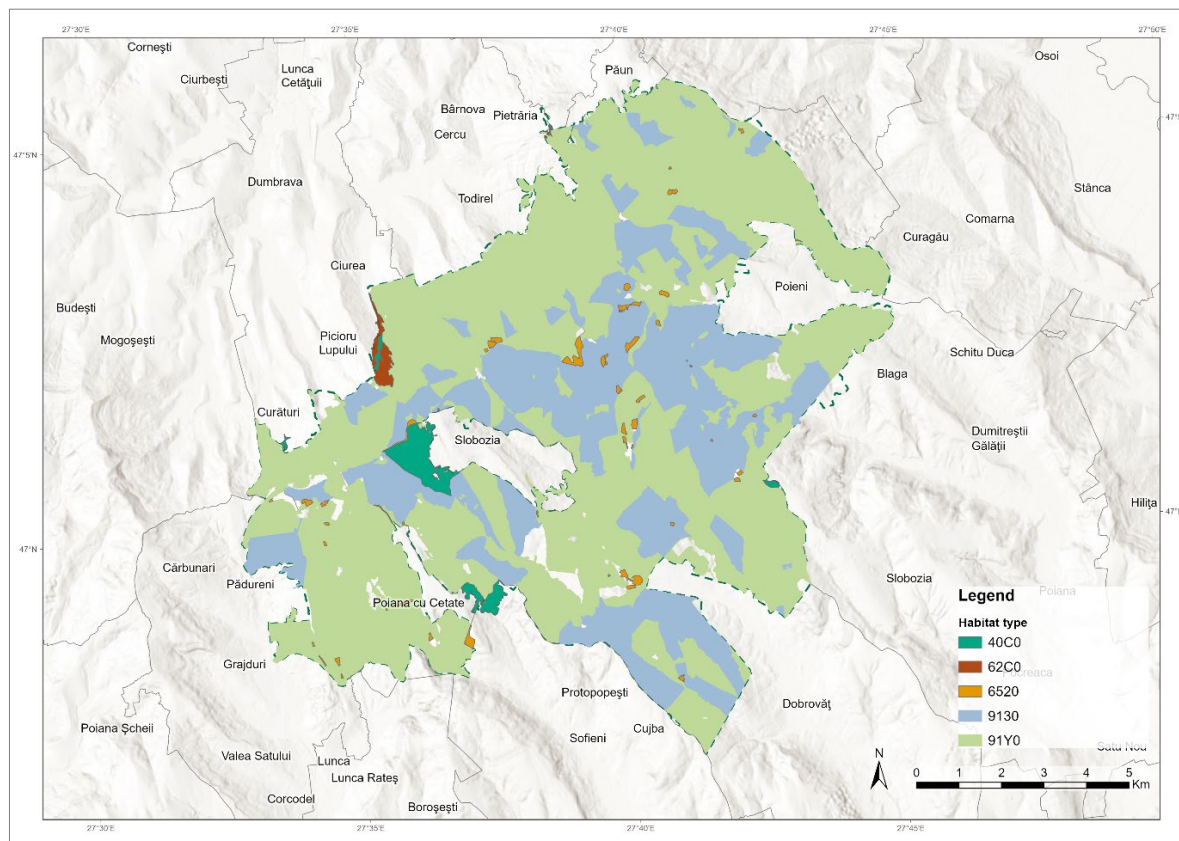


Figure 3 Habitat distribution in the study area.

The Natura 2000 sites protect a high diversity of habitats and species of European conservation interest. Forest ecosystems are dominated by habitat types 91Y0 (Dacian oak and hornbeam forests) and 9130 (*Asperulo-Fagetum* beech forests), which provide suitable habitats for numerous plant, mammal and bird species. Among the protected species recorded within the study area are the lady's slipper orchid (*Cypripedium calceolus*), the alpine longhorn beetle (*Rosalia alpina*), and more than 120 bird species, including 33 species of Community interest, such as the Eurasian eagle-owl (*Bubo bubo*) (Stoica et al., 2017).

The forest composition within the study area is dominated by broadleaved species, particularly *Fagus sylvatica* (beech), *Carpinus betulus* (hornbeam), *Tilia cordata* (small-leaved lime), *Quercus petraea* (sessile oak), and *Quercus robur* (pedunculate oak), which form mesophilous and thermophilous forest stands typical of the high hills of the Central Moldavian Plateau. *Fagus sylvatica* and *Carpinus betulus* are the most widespread species and, together with *Quercus petraea*, define the characteristic forest communities associated with the Natura 2000 habitat types 9130 (*Asperulo-Fagetum* beech forests) and 91Y0 (Dacian oak and hornbeam forests).

Over the past three decades, *Tilia cordata* has expanded considerably, occupying large areas, particularly within managed forests, where it has been promoted through both natural regeneration and planting. This expansion is largely attributed to its broad ecological adaptability, rapid growth rate, and frequent use in reforestation programmes, despite its lower economic value compared with traditional hardwood species. In many areas, *Tilia cordata* has successfully established where the regeneration of oak and beech was limited or unsuccessful due to site degradation, insufficient seed sources, soil compaction, or excessive grazing, factors that have reduced the natural regeneration capacity of these more demanding species.

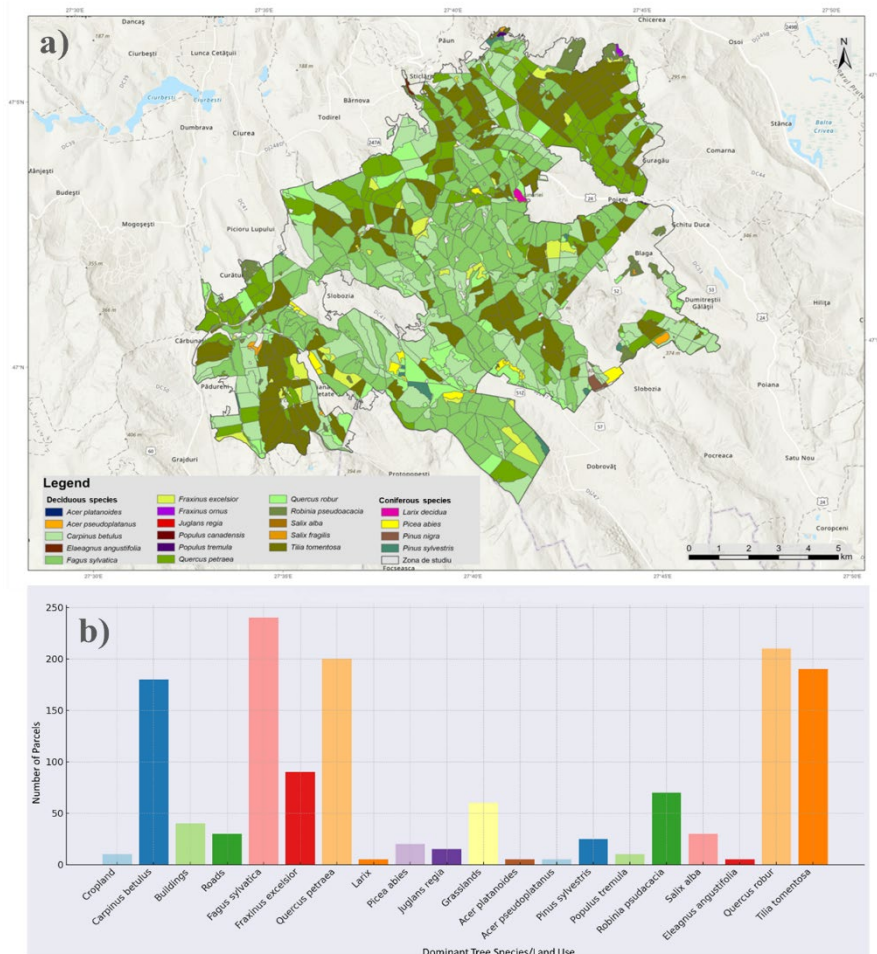


Figure 4 Spatial distribution of dominant tree species in the study area (a) and the corresponding plot distribution by (b)

In addition to the dominant species, other broadleaved trees occur in smaller proportions, including *Fraxinus excelsior* (ash), *Acer pseudoplatanus* and *Acer platanoides* (maples), *Robinia pseudoacacia* (black locust), *Betula pendula* (silver birch), *Populus spp.* (poplars), and *Salix spp.* (willows), each generally accounting for less than 5% of the total forest area. Small plantations of artificially introduced species, such as *Larix decidua* (European larch), are also present within the study area (Donisă et al., 2006).

2.2 Data Processing and Analysis

This study used Sentinel-2 satellite imagery for the period 2017–2024, acquired from the Copernicus Open Access Hub, along with ERA5 Land meteorological data sourced from Copernicus Climate Data Store. The satellite images were preprocessed at the Bottom-of-Atmosphere (BOA) level to reduce atmospheric interference. ERA5 Land data, with a $0.1^\circ \times 0.1^\circ$ resolution, provided variables such as temperature, precipitation, and solar radiation (Hersbach et al., 2020).

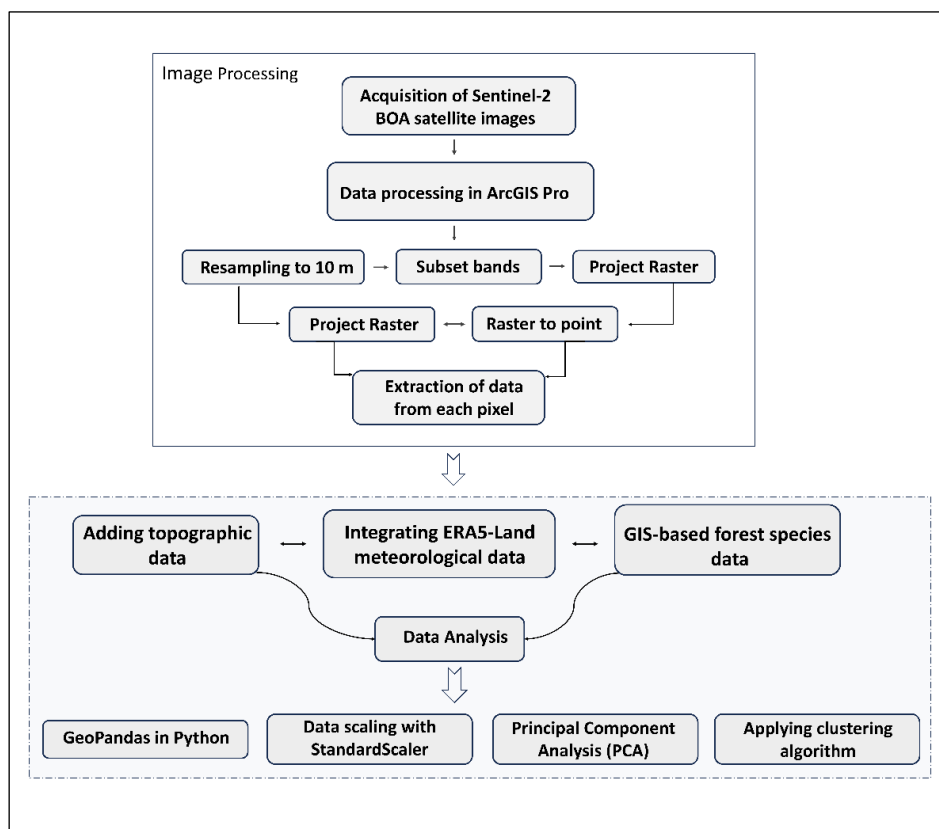


Figure 5 Data processing and analysis workflow

Sentinel-2 Level-2A images (Bottom-of-Atmosphere reflectance) were preprocessed and analyzed using ArcGIS Pro 3.1 and Python. We resampled relevant spectral bands to 10 m resolution and generated false-color composites for quality checks. NDVI was calculated for each image using the NIR (near-infrared) and red bands (Band 8 and Band 4 respectively) following standard formulas (Huete et al., 1988; Gao, 1996). The NDVI maps represent vegetation greenness and density, ranging from -1 to 1 (with higher values indicating more vigorous green vegetation). From each year's NDVI raster, we extracted the values corresponding to known forest inventory plots and dominant tree species locations. Using a raster-to-point sampling method, NDVI values were sampled for points representing stands of particular species or habitat types, based on a GIS layer of forest stand data. This allowed linking NDVI data with specific tree species (e.g. plots dominated by *Quercus petraea* or *Acer platanoides*) and with the two main habitat classes (91Y0 vs 9130).

High-resolution topographic data were incorporated to account for terrain effects on vegetation. A 5 m digital elevation model (DEM) was used to derive slope (in degrees) and aspect (cardinal direction of slope exposure) for the study area. Each NDVI sample point was attributed with its underlying slope and aspect from the DEM. Aspect

values were transformed into numeric classes (e.g. north, east, south, west in degrees) for analysis. We also integrated the ERA5-Land climate variables by interpolating monthly averages of precipitation, soil temperature, and solar radiation to the local scale. This yielded gridded climate surfaces at ~1 km resolution, which were then sampled to each point corresponding to the timing of satellite acquisitions (e.g. August 2019 climate values for the August 2019 NDVI image). By combining these layers, we built a comprehensive dataset for analysis, with each point featuring NDVI along with associated species, habitat, slope, aspect, and climate attributes.

We employed statistical techniques to explore relationships in the compiled dataset. Spearman's rank correlation was used to evaluate associations between NDVI and environmental variables, chosen due to its robustness against non-normal data distributions. Correlation matrices were computed for selected representative periods (for example, peak summer of a dry year vs a wetter early summer) to compare how climate-NDVI relationships may vary seasonally. To identify patterns among tree species, we performed a cluster analysis on the average NDVI values. A hierarchical clustering (Ward's method on Euclidean distances) was applied to group tree species by their NDVI profiles, revealing similarities in vegetative density among species.

A simple linear regression was applied to the NDVI time series for each pixel in order to calculate the NDVI trend. The formula used for calculating the slope (m) of the linear trend is as follows:

$$m = \frac{N \sum(x \cdot y) - \sum x \cdot \sum y}{N \sum(x^2) - (\sum x)^2}$$

where:

- m is the slope of the NDVI trend,
- N is the number of years (in this case, 8),
- x represents the time index (1 for 2017, 2 for 2018, *until* 8 for 2024),
- y is the NDVI value for each pixel in each year.

The calculated slope for each pixel indicates the rate of change in NDVI over time: positive slope values suggest an increase in vegetation density, while negative slope values indicate a decrease.

The results were visualized through thematic maps and graphs generated in Python. The maps depicted spatial and temporal patterns of vegetation changes, while graphs highlighted the relationships between vegetation indices and climatic variables, offering insights into the seasonal dynamics of forest vegetation.

3. Results

The analysis of vegetation dynamics in the Bârnova-Repedea Forest, based on Sentinel-2 satellite imagery from 2017 to 2024, revealed clear patterns of NDVI variation correlated with climatic and topographic factors.

NDVI values were extracted for summer months (particularly August) due to the peak photosynthetic activity and vegetative density during this period. These values were

subsequently compared with meteorological and topographic variables, including temperature, precipitation, solar radiation, slope, and aspect.

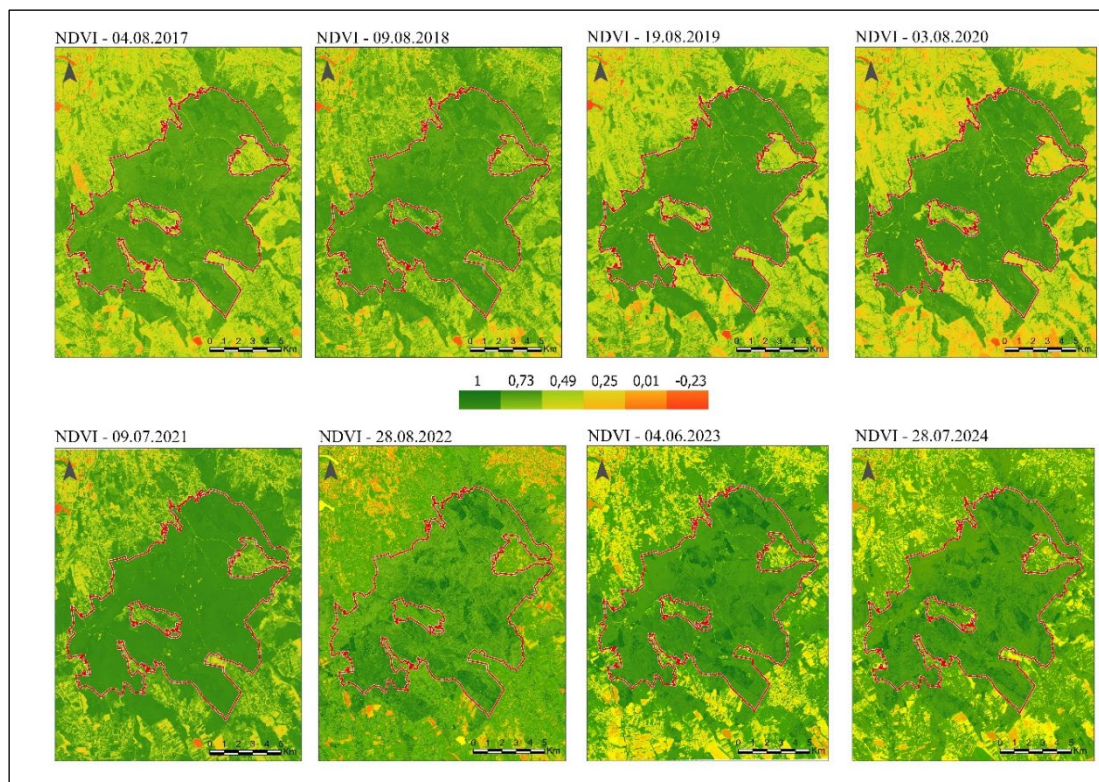


Figure 6 NDVI maps for the summer months from 2017 to 2024 in the Bârnova-Repedea Forest

Average NDVI values calculated for individual tree species revealed clear differences, emphasizing variability in vegetative health across the study area. Species with higher NDVI values, such as *Acer platanoides* (Norway maple) and *Fagus sylvatica* (European beech), reflected dense canopies and a strong capacity to adapt to local environmental conditions. In contrast, lower NDVI values were recorded for *Salix alba* (white willow) and *Tilia tomentosa* (silver lime), indicating greater susceptibility to stress factors such as prolonged drought or elevated temperatures. The NDVI maps spanning 2017 to 2024 (Figure 6) show that most of the forest maintained stable and healthy vegetation conditions over time. Nonetheless, localized declines were observed in certain areas, particularly on steeper slopes or south-facing aspects, where environmental stress is likely more pronounced. The Spearman correlation matrix (Figure 7) was used to analyze the relationships between NDVI and climatic variables for two distinct periods: August 2019 and June 2023.

Correlations indicated that solar radiation, a critical factor for photosynthesis, showed a significant positive correlation with NDVI ($r = 0.71$, $p < 0.05$). Precipitation also had a moderate positive effect on NDVI ($r = 0.45$, $p < 0.05$), emphasizing the importance of soil water availability for tree health. In contrast, temperature exhibited a weak negative correlation with NDVI ($r = -0.12$, $p < 0.05$), suggesting that elevated temperatures can slightly negatively impact vegetation health by increasing thermal stress.

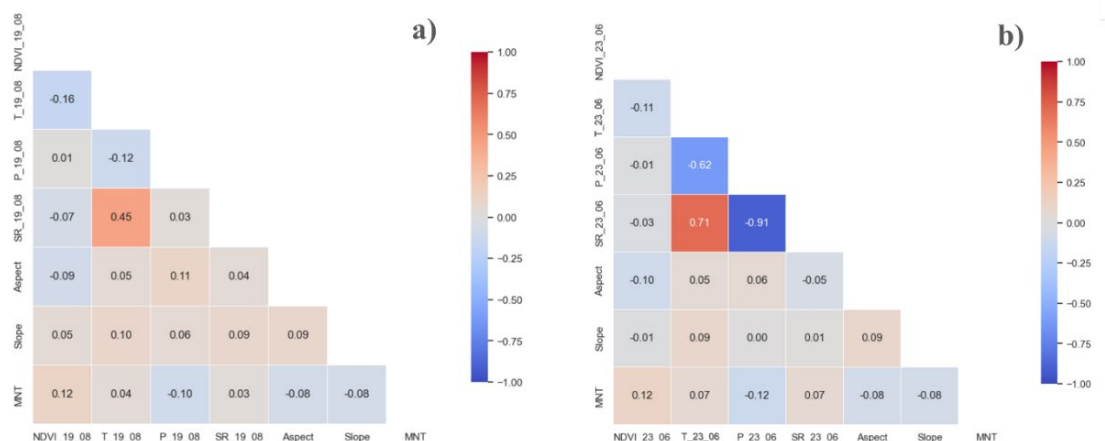


Figure 7 Spearman correlation matrices between NDVI and environmental variables for two representative periods: (a) August 2019 and (b) June 2023.

The analysis of these two months highlighted subtle variations in vegetation health between the periods, underscoring the influence of seasonal climatic factors on NDVI values. In August, when temperatures reach higher levels and precipitation is significantly lower, vegetation experiences moderate thermal stress, reflected in a slight decline in NDVI. This phenomenon may be associated with soil water deficits and the intensity of solar radiation, which place additional pressure on vegetation's photosynthetic processes. In contrast, June, characterized by milder climatic conditions, with more moderate temperatures and more frequent rainfall, fosters vegetation development, resulting in higher NDVI values.

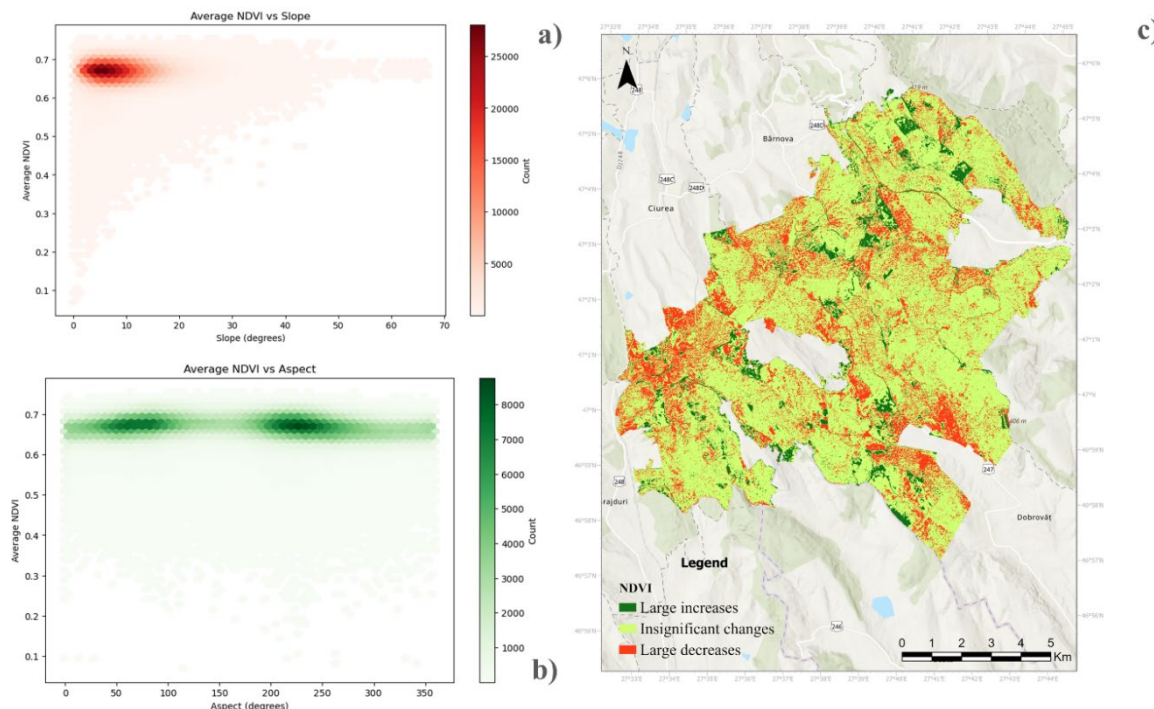


Figure 8 Relationships between average NDVI and terrain factors (a, b) and spatial distribution of NDVI changes in the study area (c).

NDVI values were higher on gentle slopes, ranging from 0 to 10°, where vegetation remains dense and healthy.

As the slope increases, NDVI gradually decreases, indicating a negative relationship between terrain inclination and vegetative density. Additionally, slope aspect moderately influenced the distribution of NDVI. The highest values were recorded on east-facing (67.5° – 112.5°) and west-facing slopes (247.5° – 292.5°), benefiting from optimal light exposure. In contrast, south-facing slopes exhibited lower NDVI, suggesting that in these shadier areas, NDVI values are reduced, or that shading itself influenced the results obtained from this analysis. These findings indicate that the observed variations in NDVI can be influenced by topographic factors and, to some extent, by meteorological factors.

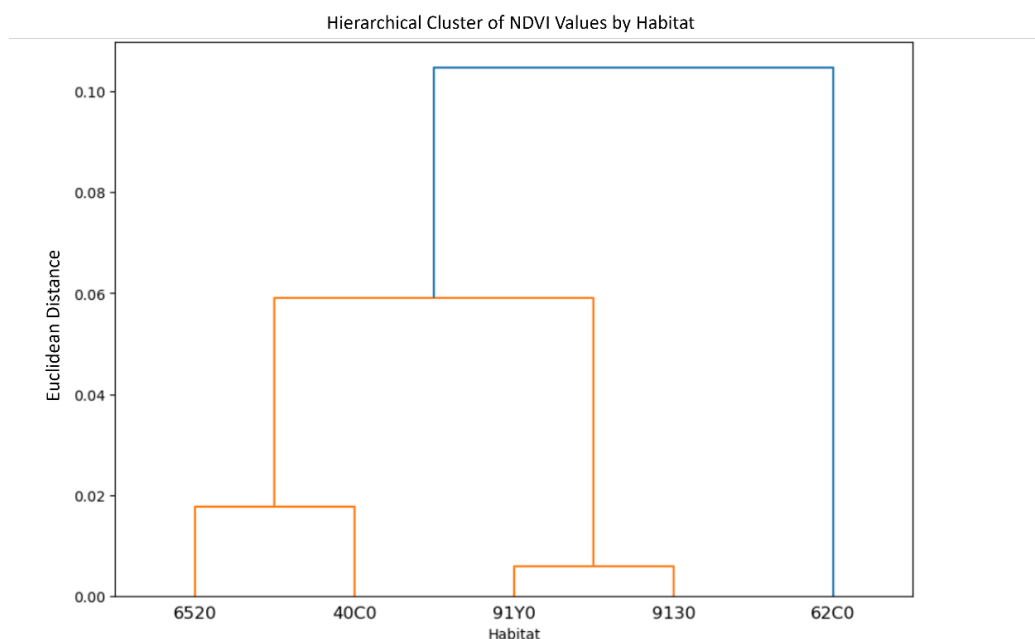


Figure 9 Hierarchical clustering dendrogram of tree species based on NDVI.

This study also included a hierarchical clustering dendrogram (Figure 9), which identified distinct groups of tree species based on similar NDVI values. The chart illustrates the results of a hierarchical clustering of NDVI values for tree species in the analyzed area, highlighting their similarities and differences in terms of vegetative density. Three main groups were observed: the first group, consisting of species such as *Pinus sylvestris* (Scots pine), *Larix* (larch), and *Salix alba* (white willow), shows similar NDVI values, reflecting comparable vegetative structure and adaptability to local conditions.

The second group includes species such as *Tilia tomentosa* (silver lime), *Fraxinus excelsior* (ash), and *Quercus petraea* (sessile oak), which display intermediate NDVI values, indicating moderate vegetative density. The last group, composed of *Acer pseudoplatanus* (sycamore maple) and *Acer platanoides* (Norway maple), is characterized by higher NDVI values, suggesting better vegetative health or a denser canopy. These differences reflect variations in the species' responses to local environmental factors and their specific physiological characteristics.

In addition to species-based clustering, we analyzed NDVI patterns by habitat type to see how the protected forest habitats compare with other land cover types. The dendrogram below illustrates the clustering of mean NDVI for the main habitat categories present. We found that the two target forest habitats: 91Y0 Dacian oak-hornbeam forests and 9130 *Asperulo-Fagetum* beech forests group very closely

together, essentially forming one cluster characterized by relatively high NDVI. This suggests that these mature deciduous forests have broadly similar greenness levels and phenology, which is expected given that they are both closed-canopy, broadleaf-dominated habitats. On the other hand, open or non-forest habitats in the area (6520, 40C0 and 62C0) showed lower NDVI values and clustered separately from the two forest habitats.

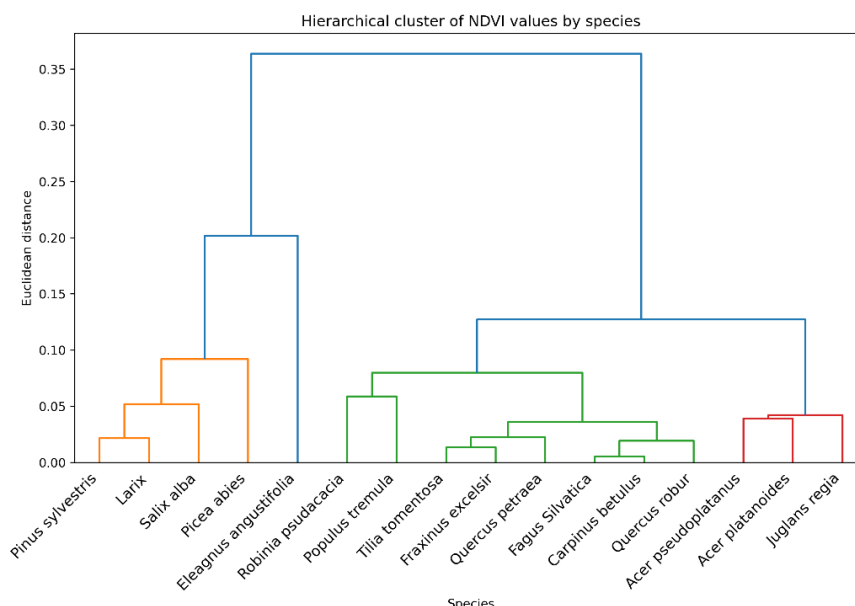


Figure 10 Hierarchical clustering of average NDVI by habitat type (dendrogram with habitat codes)

Habitats 6520 and 40C0 formed a cluster indicative of sparse vegetation cover, while habitat 62C0 was even more distinct due to its very low, patchy vegetation. This habitat-based clustering confirms that the forested habitats (91Y0, 9130) maintain high vegetation density relative to surrounding non-forest habitats. It underlines the role of these forests as oases of productivity and biomass in the landscape, as opposed to the more open habitats which, while biodiversity-rich in their own right, have lower NDVI by virtue of less canopy cover. The clustering results by habitat validate our approach of using NDVI as a proxy for habitat condition: protected forest habitats stand out clearly from secondary habitats in terms of greenness.

4. Conclusions

The study conducted on the Bârnova-Repedea Forest, a protected area within the Natura 2000 network, demonstrated the usefulness of integrating remote sensing and GIS analysis in monitoring vegetation dynamics and forest ecosystem health. The NDVI analysis, based on Sentinel-2 satellite imagery from 2017–2024, revealed spatial and temporal variations in vegetative density, influenced by climatic and topographic factors. The predominant forest habitats, 9130 (*Asperulo-Fagetum* beech forests) and 91Y0 (Dacian oak and hornbeam forests), showed species-specific differences. *Acer platanoides* and *Fagus sylvatica* exhibited high NDVI values, indicating superior vegetative health, while *Salix alba* and *Tilia tomentosa* had lower values, suggesting higher sensitivity to local conditions such as drought or elevated temperatures.

The analysis using topographic data highlighted that gentle slopes (0–10°) and east and west facing slopes are favorable for higher vegetative density, while south-facing slopes, exposed to higher temperatures and drier conditions, recorded lower NDVI

values. Climatic correlations demonstrated a positive influence of solar radiation and precipitation on vegetation health, emphasizing the importance of water availability and light for photosynthetic processes, while elevated temperatures had a moderately negative effect.

Species clustering based on NDVI values revealed distinct groups, reflecting variations in their responses to environmental conditions. Groups with higher values, such as *Acer pseudoplatanus*, *Acer platanoides*, and *Juglans regia*, highlighted adaptability to local environmental conditions, while other species, such as *Pinus sylvestris* and *Larix*, indicated more homogeneous vegetative structures.

Overall, this study demonstrates the value of integrating multi-temporal Sentinel-2 imagery with forest management plans, habitat distribution and environmental variables to assess vegetation dynamics in a Natura 2000 protected forest. The combined use of remote sensing, GIS analysis and forest inventory data enabled the identification of species- and habitat-specific vegetation patterns, as well as their relationships with topographic and climatic factors. The proposed approach provides a practical framework for long-term monitoring of protected forest ecosystems and can support conservation planning and adaptive forest management in Natura 2000 sites.

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