Examining Vegetation Deterioration in the Carpathian Mountains Using Survival Analysis

Melinda Manczinger [1,], Tibor Kovács[2]*

[1] Doctoral School of Economics and Business Informatics, Corvinus University of Budapest, Budapest, 1093, Hungary, melinda.manczinger@uni-corvinus.hu

[2] Department of Information Systems, Institute of Data Analytics and Information Systems, Corvinus University of Budapest, Budapest, 1093, Hungary, tibor.kovacs@uni-corvinus.hu

* corresponding author

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Abstract: Vegetation condition is a key indicator of ecosystem stability and fire susceptibility in mountain landscapes. Using monthly Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) (2000-2024) for 223,811 vegetated H3 hexagons in the Carpathians, we applied survival analysis to quantify when sustained NDVI deterioration first occurs and how its timing varies with Natura 2000 protection and land cover. After defining a 2003-2008 mean NDVI baseline and identifying persistent deterioration as runs of negative anomalies during the growing season, we estimated Kaplan-Meier curves and log-rank tests. Across all countries, Natura 2000 sites showed higher survival probabilities and thus a lower hazard of persistent NDVI decline than non-protected areas, although the effect was dependent on land cover type and examined countries. Agricultural vegetation deteriorated later than forest and semi-natural vegetation. These time-to-deterioration metrics could provide additional insight to understand the drivers of vegetation decline in the Carpathians.

Keywords: Carpathians; vegetation deterioration; NDVI; survival analysis; Natura 2000.

1 Introduction

Vegetation condition is a key indicator of ecosystem functioning and disturbance response. In the Carpathians, tracking vegetation deterioration is relevant not only for ecological assessment, but also because vegetation stress is closely linked to fire susceptibility (Manczinger et al. 2025). Remotely sensed indices such as NDVI provide an efficient basis for monitoring these dynamics consistently across large areas and long time periods. However, NDVI time series are inherently noisy and sensitive to atmospheric effects, cloud contamination, seasonal variability, and data gaps, so careful preprocessing is required before they can be used to detect meaningful ecological change (Cao et al. 2018, Chen et al. 2004, Hird and McDermid 2009).

Partly for this reason, most NDVI-based studies have focused on long-term trends, break points, or average changes in vegetation condition (Chen et al. 2018, Eckert et al. 2015, Forkel et al. 2013, Furusawa et al. 2023, Santana 2018), whereas the timing of sustained vegetation deterioration has received comparatively little attention (Bianchi et al. 2019, Hurley et al. 2014, Pereira et al. 2018). Survival analysis is well suited to this problem because it models the time until a defined event occurs (here: persistent NDVI deterioration), while accounting for units that do not experience the event within the study period (right-censoring) (Denfeld et al. 2023). Although survival methods are well established in medical sciences and have been used in some environmental applications, including deforestation and forest decline (Augustin et al. 2025, Dhakal et al. 2023, Greenberg et al. 2005, Kitikidou and Apostolopoulou 2011), they remain rare in large-scale, remotely sensed vegetation monitoring.

Here, we apply survival analysis to monthly MODIS NDVI time series to examine whether and when sustained vegetation deterioration occurs across the Carpathian region and how its timing varies with protection status and land cover context. Specifically, we ask whether the timing and likelihood of deterioration differ between protected and non-protected areas, and whether these patterns vary among major land cover types. We hypothesise that vegetation within Natura 2000 sites has a lower risk of persistent NDVI decline than vegetation outside protected areas, and that this protective effect is strongest in forested land cover types, where lower anthropogenic pressure, more regulated management, and reduced land use conversion may promote greater ecosystem stability and resilience.

2 Materials and methods

2.1 Study area and spatial framework

The study covered the Carpathian Mountain chain, spanning 39 administrative regions in Czechia, Hungary, Poland, Romania, Serbia, Slovakia, and Ukraine. The spatial framework was based on the H3 hierarchical hexagonal grid system, using cells at resolution 8 with an area of approximately 0.74 km^2. In total, 386,885 hexagons were generated and used as units for NDVI time series extraction.

2.2 Land cover

Land cover information was taken from the 2018 CORINE Land Cover (CLC) 100 m status layer. CLC classes were aggregated to the H3 grid to identify the dominant class in each hexagon. From the 44 thematic classes, we retained only vegetation-related categories: agricultural vegetation (classes 12-22), forests and semi-natural vegetation (23-29), and wetland vegetation (35-37). To focus on clearly vegetated pixels, we kept only hexagons fully covered by these classes, yielding 223,811 units for survival analysis.

2.3 Vegetation index

NDVI time series were extracted at hexagon centroids using NASA's AppEEARS interface (version 3.71) from the Terra MODIS MOD13A3 v6.1 product (monthly NDVI, 1 km resolution). The series span 1 February 2000 to 31 December 2024, providing 299 monthly observations per hexagon before preprocessing.

2.4 Protection status

Natura 2000 site boundaries were obtained from the European Environment Agency data hub for the period 2010-2023, including both Special Areas of Conservation and Special Protection Areas. Coverage was assessed for EU member states in the study area (Czechia, Hungary, Poland, Romania, and Slovakia). Hexagons whose centroid fell within any Natura 2000 polygon were classified as protected, all others were treated as non-protected.

2.5 NDVI preprocessing

Monthly NDVI values were extracted at the centres of vegetated hexagons, and all preprocessing was performed separately for each hexagon. First, time series were screened using the MODLAND pixel reliability layer: observations flagged as good or marginal quality were retained, whereas values affected by clouds, snow, or missing data codes (-3000) were treated as missing. Following MODLAND definitions, good quality pixels represent highest reliability observations, while marginal quality indicates acceptable data that could also be used inspecting other quality indicators. Missing values were imputed with a hierarchical temporal procedure. For each gap, we first searched for NDVI from the same calendar month in the preceding and following year (±1-year lag/lead). When both values were available, their mean was used, when only one was available, that value was used, otherwise, the observation remained missing at this stage. Remaining gaps were then filled with the monthly climatological mean of the corresponding hexagon, calculated over the full time series for the same calendar month.

The completed series were smoothed with a Savitzky-Golay filter to reduce short-term noise while preserving seasonal dynamics. We compared parameter combinations (window sizes 5 and 7, polynomial orders 2 and 3) against a 3-month moving average using root mean square error (RMSE) and mean absolute deviation (MAD) and selected a window of 7 and polynomial order 3 as the best trade-off between noise reduction and signal preservation. The overall preprocessing workflow is summarised in Figure 1.

2.6 Survival analysis framework

We used survival (time-to-event) analysis to quantify when sustained vegetation deterioration first occurred in each hexagon. Each H3 cell was treated as an observational unit and followed through time until the onset of persistent NDVI decline or censoring, allowing comparison of deterioration timing among land cover and protection status groups.

To define anomalies, we first established a baseline period from 2003-2008, selected because regional mean NDVI during these years showed low interannual variability (standard deviation ≈ 0.0025) and no significant linear trend (slope ≈ 0.0004 NDVI units per year, $p \approx 0.29$). For each hexagon and calendar month, we computed the mean and standard deviation of smoothed NDVI over this baseline and expressed subsequent observations as both absolute anomalies from the mean and standardized anomalies relative to the monthly standard deviation.

Sustained deterioration was defined with a multi-threshold persistence rule. Monthly NDVI was evaluated against several absolute anomaly thresholds (-0.05, -0.08, -0.10) and standardized thresholds (-1.0, -1.5, -2.0), a month was classified as unfavourable when at least two thresholds were exceeded. Event detection was restricted to the growing season (April-October), and we considered runs of 1-5 consecutive unfavourable months, an event was recorded when a hexagon experienced a run of K such months within the growing season. Survival time was defined as days from 1 January 2009 (just after the previously defined 2003-2008 mean NDVI baseline period) to the first persistent deterioration event, hexagons without an event by 1 December 2024 were right-censored.

Deterioration timing was then compared across strata defined by protection status and land cover. Hexagons whose centroid fell inside any Natura 2000 polygon were classified as protected, all others as non-protected, and land cover context was given by the dominant CLC class in each hexagon. These covariates formed the grouping variables for Kaplan-Meier curves and log-rank tests.

3 Results and discussion

3.1 NDVI reliability declines with elevation

The final dataset comprised 223,811 vegetated hexagons and 66.9 million monthly NDVI observations. Overall, most observations were of good or marginal quality, supporting the use of these NDVI series for survival analysis. Spatially, the longest consecutive gaps of low reliability observations were concentrated along the main mountain ridges, whereas short or no gaps dominated most of the study

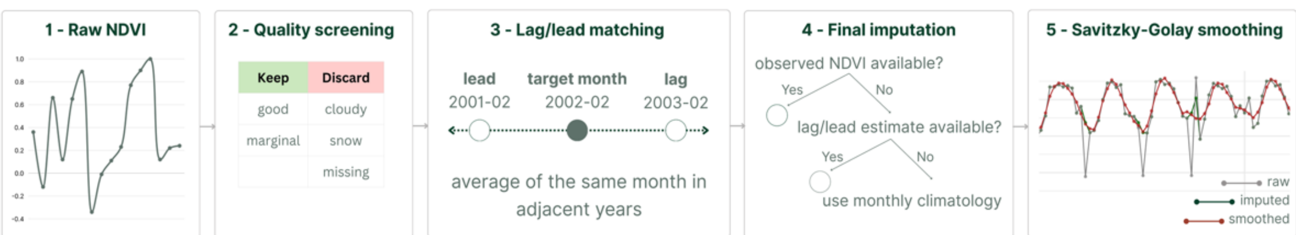

Figure 1. Methodological workflow for NDVI preprocessing.

region (Figure 2). Consistent with this pattern, gap length showed a moderate positive correlation with elevation (Spearman's $\rho = 0.435$, $p < 2.2 \times 10^{-16}$) and elevation differed significantly among gap-length categories (Kruskal-Wallis $\chi^2 = 51{,}688$, df = 9, $p < 2.2 \times 10^{-16}$) indicating that longer low reliability gaps were more common at higher elevations.

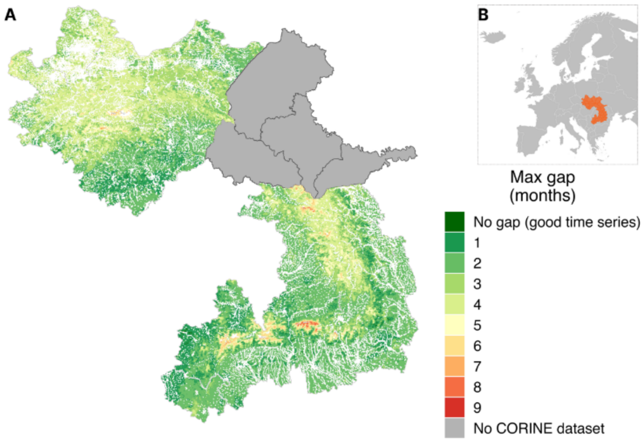

Figure 2. (A) Spatial pattern of maximum consecutive low reliability gaps by H3 hexagon. (B) The Carpathian study area within Europe.

3.2 Survival patterns of vegetation deterioration

At the aggregate level, hexagons within Natura 2000 sites showed higher survival probabilities than those outside protected areas, indicating a lower hazard of persistent NDVI deterioration over time (log-rank test, $p < 0.0001$). The curves began to diverge early (around May 2010, ≈ 500 days after the start date) and remained separated throughout the study period (Figure 3A). A similar pattern was evident in each country separately except Poland, where the survival curves were reversed but the difference was not statistically significant ($p = 0.079$). These results are consistent with NDVI-trend studies reporting more stable or greener trajectories inside protected areas, including Natura 2000 sites in Poland and nature reserves elsewhere, even though those studies focus on trend magnitude rather than time to deterioration (Mateusz and Sender 2026, Zoungrana and Dimobé 2023). They also align with findings that lower NDVI change (greater stability) is often, but not always, associated with threatened plants and protected sites, suggesting that protection can reduce – but not eliminate – the risk of vegetation decline (Matas-Granados et al. 2022).

Land cover comparisons showed that deterioration timing differed between the two major vegetation classes (Figure 3B). Across all countries, agricultural vegetation had consistently higher survival probabilities than forest and semi-natural vegetation (log-rank test, $p < 0.0001$), indicating a lower hazard of persistent NDVI decline. This pattern is plausible because cropped and managed systems typically receive more active human care during the growing season (e.g., sowing, fertilization, irrigation), which may buffer short-term stress and delay sustained NDVI reductions compared with forests and semi-natural vegetation.

When the analysis was restricted to forest and semi-natural vegetation (Figure 3C), the overall Natura 2000 effect remained detectable but weaker (all countries combined: log-rank test, $p = 0.048$). Protection was associated with significantly delayed forest deterioration in Hungary and Slovakia ($p = 0.0052$ and 0.013), whereas in Poland protected forests deteriorated at least as fast as non-protected ones ($p = 0.012$), and no clear difference emerged

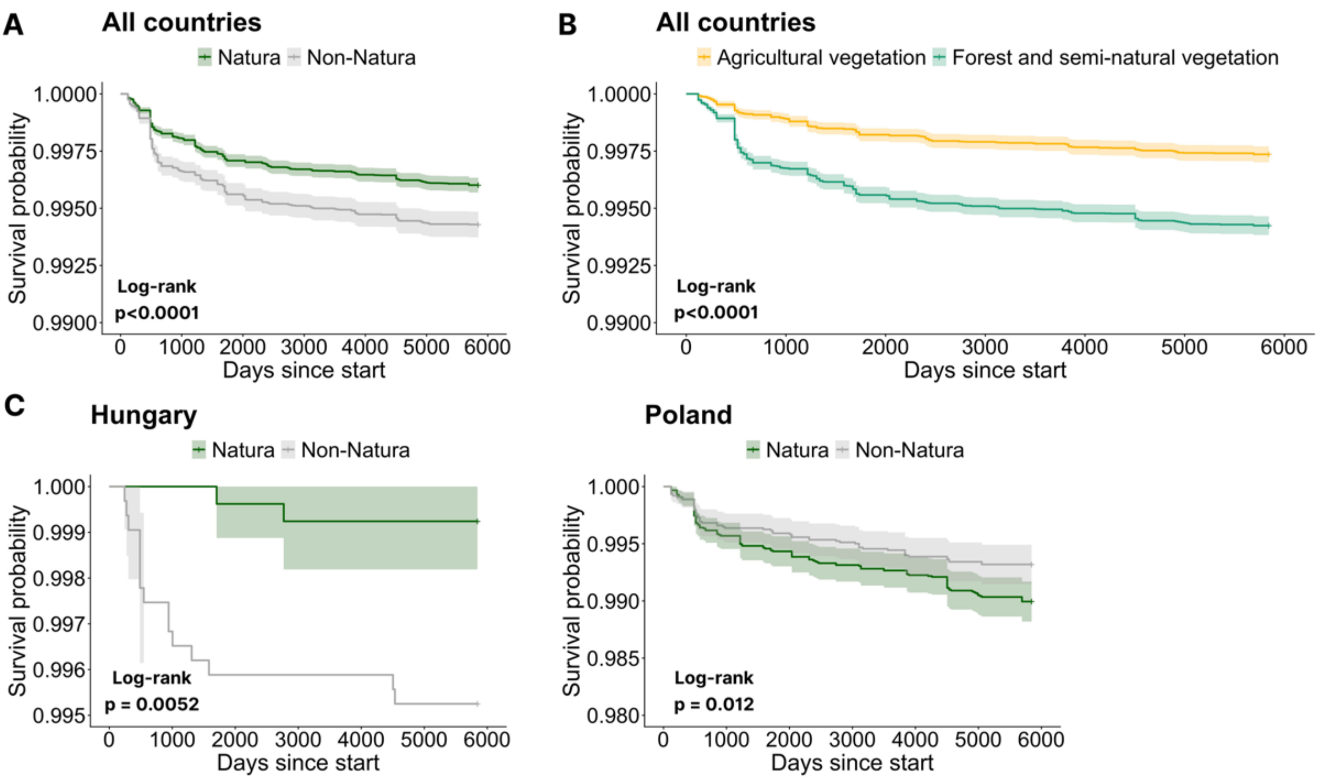

Figure 3. Kaplan-Meier curves for time to persistent NDVI deterioration by (A) protection status, (B) land cover class, and (C) protection status within forests and semi-natural vegetation.

in Romania and Czechia. Together, these patterns indicate that the effect of protection on forest deterioration timing is not spatially uniform and likely reflects country- or landscape-specific management histories, pressures, and forest types, echoing previous reports of heterogeneous NDVI trends in mountainous protected forests (Maselli 2004).

4 Conclusions

The survival analysis of MODIS NDVI suggests that persistent vegetation deterioration in the Carpathians is influenced by both protection status and land cover type, with generally lower hazards inside Natura 2000 and in agricultural areas, but heterogeneous responses in forests across countries. These findings highlight specific regions and vegetation classes where ecosystem stability is weakest and where management and policy attention may be most urgent. A natural next step is to extend the survival framework to Cox-type models that incorporate additional covariates (e.g., climate variability, topography, forest type, and management indicators) and to validate the deterioration signal using other vegetation products (e.g., Landsat-based indices). Because vegetation decline can increase fuel stress and fire risk, integrating these time-to-deterioration metrics - in the form of stability flags, hazard scores or time-to-deterioration days – with the previously developed interpretable fire susceptibility model for the Carpathians would allow a dynamic updating of fire risk layers and help identify/narrow down areas where early vegetation weakening coincides with elevated fire probability.

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