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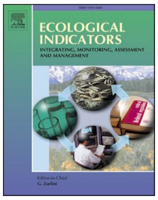

Developing National Forest Inventory-based indicators for monitoring minority ravine forests

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ABSTRACT

Ravine forests represent a priority habitat type of the European Natura 2000 network for which empirical data are limited, particularly regarding the influence of stand structure on biodiversity. Assessment of forest habitats can largely be supported by National Forest Inventory (NFI) data, which enable frequent and spatially dense monitoring of the stand conditions and potential vulnerability of forest habitat types. In this study, we established an independent, nationwide classification system of close-to-nature managed ravine forests dominated by different characteristic broadleaf trees, based on stratifying NFI data into homogeneous subtypes. On the basis of tree species composition, which is a basic component in forest habitat types, we identified three subtypes of ravine forests, dominated by *Acer pseudoplatanus*, *Fraxinus excelsior*, and *Tilia* spp. We examined these subtypes using structural, compositional, deadwood, and diversity-related indicators. The *Tilia*-dominated subtype was more common in the lower altitudinal belt ($\leq$ 502 m), while the *Acer*-dominated subtype was more prominent in the higher belt ($>$ 502 m). The *Acer*-dominated subtype predominated in stands with SDI lower than 432, while the *Tilia*-dominated subtype was relatively more common in stands with higher SDI. In stands with Evenness values lower than 0.3, the *Acer*-dominated subtype predominated, while in stands with higher Evenness index values, the *Fraxinus*-dominated subtype was more common. In the *Fraxinus*-dominated subtype, the volume of standing dead trees was statistically significantly higher than in the other two subtypes (14 m^3/ha compared to 8 m^3/ha) due to the high mortality rate of trees caused by ash dieback. In all three subtypes of ravine forests, we observed a lack of natural regeneration of key tree species, which is crucial for maintaining the favorable conservation status of the habitat type. The observed ranges of structural and compositional attributes, deadwood components, and diversity indices provide empirical reference conditions that reflect the current nationwide variability of ravine forests.

1. Introduction

Natura 2000 provides an integrated framework for identifying, maintaining, and protecting sites with high biodiversity value (Kovac et al., 2018; Velázquez et al., 2010). Achieving favorable conservation status for Natura 2000 habitats (Habitats Directive, 1992; Kovac et al., 2018) requires a comprehensive assessment of habitat quality from a nature conservation perspective. Assessment of forest habitats can largely be supported by National Forest Inventory (NFI) data (Alberdi et al., 2019; Kovac et al., 2020), which enable systematic sampling and simultaneous assessment of stand structure parameters, allowing frequent and spatially dense monitoring (Kovac et al., 2020; Pintar et al., 2024) of the stand conditions and the potential vulnerability of forest habitat types. The EU Nature Restoration Regulation (EU 2024/1991), particularly Article 4, requires Member States to implement restoration measures for forest habitat types that are not in good condition and to monitor improvements in forest ecosystem condition over time. For forest ecosystems, this monitoring also relies on a set of structural and compositional indicators, many of which can be derived directly from NFI data (EU, 2024).

Tree species composition is an important factor in the conservation status of natural habitats, as it influences habitat structure, function and

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associated species composition, and largely reflects underlying site conditions. Forest stand structure and composition are key determinants of the conservation status of forest habitats (Tinya et al., 2021). Moreover, forest structural complexity is a strong and consistent predictor of trees and woody plant species richness across forest types (Sun et al., 2025). Prior to assessing forest habitats status, it is necessary to first identify all forest sites in order to obtain reliable estimates of habitat types and subtypes (Maes et al., 2020; Vockenhuber et al., 2011). Because forest habitat subtypes differ in species composition and ecological conditions, Kovač et al. (2016) propose that heterogeneous forest habitat types should be subdivided into more homogeneous subtypes to enable appropriate stewardship and to meet the requirements of international reporting.

National Forest Inventories are conducted in many European countries and provide a fundamental source of harmonized data on forest structure, tree species composition, and dynamics (Gschwantner et al., 2019; Kovac et al., 2020; Portier et al., 2022). NFI data can be used to reliably monitor the condition and changes in forests or individual forest habitat types at 5- to 10-year intervals on a systematic grid that covers the entire country (Skudnik et al., 2021a; Skudnik et al., 2021b). With denser NFI sample grids, such as in Slovenia, where the systematic sampling grid was increased from 4 × 4 km to 2 × 2 km in 2020 (Pintar et al., 2024), NFIs are also becoming a useful tool for monitoring the status of priority forest habitat types listed in Annex I of the Habitats Directive (Habitats Directive, 1992), for which data is severely lacking. This also applies to ravine forests classified as the EU priority habitat type *Tilio-Acerion* (Kutnar et al., 2025). This habitat type has been documented in 21 EU Member States and is present in 2323 designated Natura 2000 sites, covering approximately 2800 km^2 across EU (EEA, 2025; Kutnar et al., 2025). The reliability of indicators derived from NFI data depends heavily on the number of sample plots representing a given forest type, as sampling uncertainty increases when few plots are available (Cochran, 1977; Tomppo et al., 2010). This limitation is especially relevant for spatially limited or azonal forest habitat types, which often occur in small, fragmented patches that are less effectively captured by systematic sampling grids.

Both in Slovenia and across Europe, ravine forests represent a habitat type for which empirical data are limited, particularly regarding the influence of stand structure on biodiversity. Research on their status and associated indicators remains relatively fragmented (Baran et al., 2018; Baran et al., 2020; Kutnar et al., 2025). Forest stand structure indicators are important for identifying European priority forest habitat type *Tilio-Acerion* forests (9180*) (EC, 2013; Kutnar et al., 2025), including indicators related to tree species composition, growing stock, stand structure, density, and deadwood volume. Ravine forests often occur in small, fragmented patches and are therefore particularly vulnerable to environmental pressures. Key threats include climate change, habitat fragmentation, browsing by ungulates, and the decline of key tree species caused by pests and pathogens (Dakskobler et al., 2013; Kutnar and Dakskobler, 2014; Kutnar et al., 2025). Furthermore, assessing forest habitat types across large areas is a complex task. This is especially relevant when the target habitat is limited in area and displays high natural heterogeneity. Consequently, most previous studies of these forests (Kermavnar et al., 2023; Kovač et al., 2016) have focused on analyses at specific study sites rather than at the regional or national scale. A denser systematic sampling grid, and consequently a larger number of sample plots in Slovenia, enables for the first time a national-level investigation of the structure and composition of minority forest habitat types, including ravine forests of the European priority habitat type *Tilio-Acerion*.

The main objective of this study was to establish an independent, nationwide classification of close-to-nature managed ravine forests dominated by different characteristic broadleaf tree species, based on tree species composition, and to categorize these forests into homogeneous subtypes. In the studied forests, a continuous cover forestry approach is practiced to maintain a permanently irregular stand structure, created and sustained by selecting and harvesting individual trees or small groups, resulting in uneven-aged forest stands. Such management practices, including selective logging, group selection, and small-scale irregular shelterwood, promote biodiversity by increasing structural heterogeneity, maintaining favorable microclimatic conditions through the preservation of clusters of old, mature to over-mature trees, and increasing the variability of substrates and small-scale habitats, including coarse woody debris (Diaci, 2021; Kutnar et al., 2023). Given the limitations of NFI data, which primarily record tree-layer characteristics, the classification approach in this study focuses on tree species composition as an operational indicator for distinguishing and describing ravine forest stand types at the national level. The selected characteristic tree species and their dominance thresholds are based on observations from detailed studies of ravine forests in Slovenia, where dendrometric measurements and phytosociological surveys were conducted on reference plots (Kermavnar et al., 2023; Kutnar et al., 2025). Most of these forests belong to the European priority habitat type of *Tilio-Acerion* forests of slopes, screes and ravines, although similar species compositions may also occur in other forest communities (Dakskobler et al., 2013). We aim: i) to derive empirically based structural, compositional, deadwood, and diversity-related indicators of these subtypes and their reference values (to quantify the current variability of key habitat indicators) to support assessment and monitoring of ravine forests in the absence of predefined reference conditions; ii) to interpret these differences using conditional inference trees to identify statistically supported ecological, compositional, and structural thresholds differentiating those subtypes; iii) and to examine the composition of the regeneration layer to provide a future perspective on potential compositional trajectories of the identified stand types.

2. Methods

2.1. Study area and the description of ravine forests

Slovenian forests cover a total area of 1.2 million ha, which corresponds to 58% of the country's total area (SFS, 2024) (Fig. 1). Due to its heterogeneous relief, climate, and the legacy of former forest management, Slovenian forests form a diverse mosaic of forest types, ranging from lowland floodplain forests to widespread mesic mixed forests dominated by beech at medium altitudes, and to mountainous coniferous forests at higher altitudes.

In Slovenia, ravine forests are classified as Illyrian ravine forests (Chytrý et al., 2020; EEA, 2022) which encompass numerous forest associations of the Central-European alliance *Tilio–Acerion* (Bončina et al., 2021; Dakskobler et al., 2013; Kutnar et al., 2012). According to synsystematic classification in Slovenia, these ravine forests are divided into three suballiances: *Lunario-Acerenion, Lamio orvalae-Acerenion* and *Ostryo-Tilienion* (Dakskobler et al., 2013). The following associations were described, grouped by dominant tree species: *Acer pseudoplatanus* – groups i) and ii), *Fraxinus excelsior* – group iii), and *Tilia* spp. – group iv):

i) *Corydalido cavae-Aceretum pseudoplatani* var. geogr. *Dentaria enneaphyllos*, *Lamio orvalae-Aceretum pseudoplatani*, *Omphalodo vernae-Aceretum pseudoplatani*, *Dentario polyphyllae-Aceretum pseudoplatani*, *Lamio orvalae-Fraxinetum excelsioris*, *Cardamino enneaphylli-Aceretum pseudoplatani*;
ii) *Dryopterido affini-Aceretum pseudoplatani* var. geogr. *typica*, *Dryopterido affini-Aceretum pseudoplatani* var. geogr. *Dentaria trifolia*, *Dryopterido affini-Aceretum pseudoplatani* var. geogr. *Omphalodes verna*;
iii) *Hacquetio-Fraxinetum excelsioris* var. geogr. *Dentaria pentaphyllos*, *Hacquetio-Fraxinetum excelsioris* var. geogr. *typica*, *Arunco-Aceretum pseudoplatani* var. geogr. *Dentaria enneaphyllos*;
iv) *Saxifrago petraeae-Tilietum platyphylli, Corydalido ochroleucae-Aceretum pseudoplatani, Tilio cordatae-Aceretum pseudoplatani, Paeonio officinalis-Tilietum platyphylli, Veronico sublobatae-*

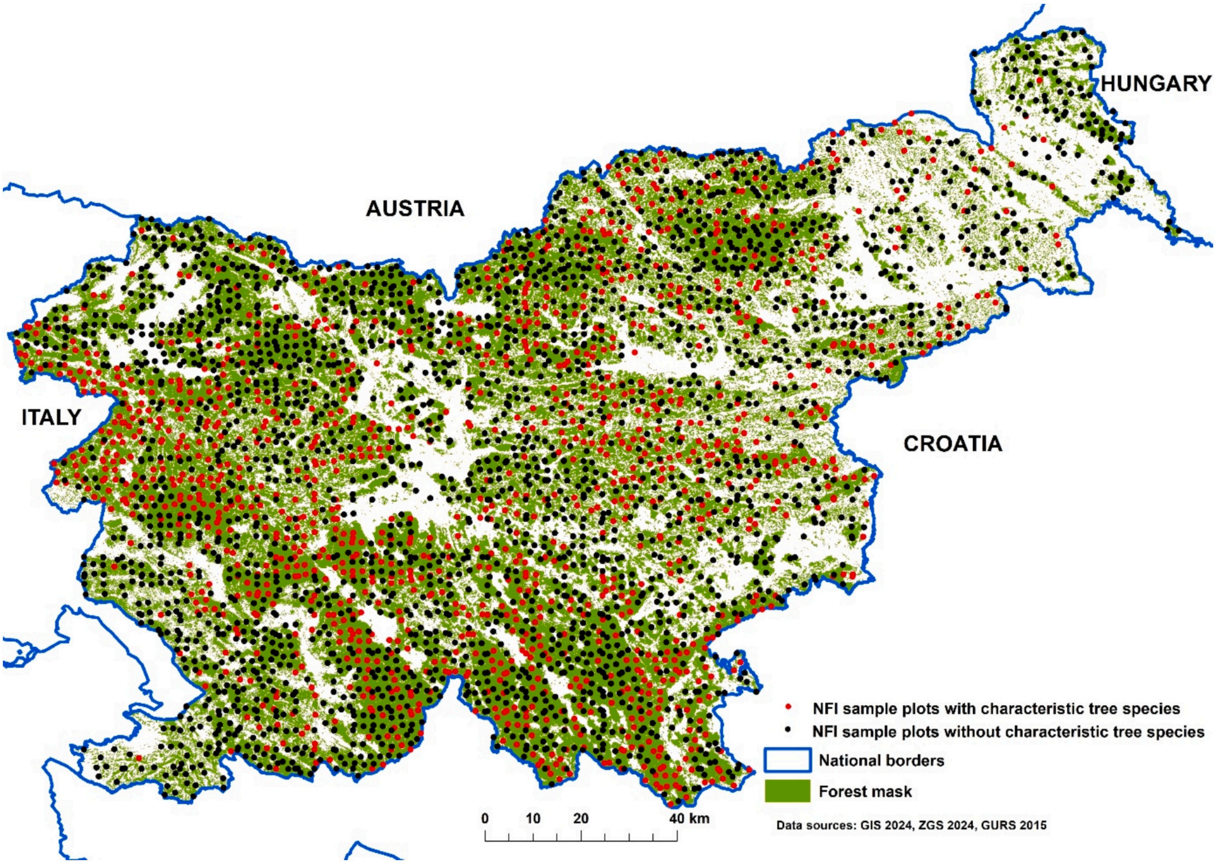

Fig. 1. Distribution of systematically located NFI sample plots measured between 2020 and 2024 across Slovenia, indicating plots where characteristic tree species of ravine forests were recorded.

> *Fraxinetum excelsioris, Veratro nigri-Fraxinetum excelsioris, Viburno opuli-Tiletum cordatae, Crepido paludosae-Ostrytum carpinifoliae*.

Diagnostic species of the alliance *Tilio-Acerion* are following: *Acer pseudoplatanus*, *A. platanoides*, *Tilia platyphyllos, T. cordata*, *Ulmus glabra*, *Fraxinus excelsior*, *Lunaria rediviva*, *Arum maculatum*, *Aruncus dioicus, Staphylea pinnata, Euonymus latifolia, Polystichum aculeatum*, *Phyllitis scolopendrium, Scrophularia vernalis and Polystichum braunii* (Dakskobler et al., 2013). They occur under a wide range of site conditions and reflect a broad ecological amplitude (Bončina et al., 2021; Dakskobler et al., 2013; Kutnar et al., 2012). The investigated ravine and similar forests dominated by selected species (*Acer* spp., *Fraxinus excelsior*, *Tilia* spp. and others), are highly heterogeneous. There has been no detailed mapping of these forests across the entire country. Previous studies in the Boč–Haloze–Donačka Gora area have identified four habitat subtypes based on dominant tree species and site conditions, including i) *Acer pseudoplatanus* stands admixed with *Ulmus glabra* grow mostly in the concave terrain, ii) *Acer pseudoplatanus* stands with an admixture of *Castanea sativa* occur on more acidic soils, iii) *Fraxinus excelsior* stands frequently occur on slopes, and iv) *Tilia platyphyllos* and *Tilia cordata* stands with thermophilous broadleaves thrive mostly on exposed ridges and slopes (Kermavnar et al., 2023). In the study of Kermavnar et al. (2023) the largest mean slope was measured for *Tilia* stands.

In this study, *Acer*-dominated subtypes on less acidic soils (*Acer* stands with *Ulmus*) and more acidic soils (*Acer* stands with *Castanea*) were merged because they cannot be reliably separated based solely on tree species composition in NFI data.

Ravine forests are usually found in small patches in stony or rocky gullies, dolines, ravines, torrential fans, gravelly slopes, moist rock formations, and sun-exposed ridges. These forests occur at altitudes ranging from the colline to the altimontane vegetation belt (Dakskobler et al., 2013). The soils in these forests are primarily colluvial-deluvial, with occasional rendzina and brown calcareous soil formations. Litter decomposition is relatively rapid, resulting in high nutrient availability. Some stands occur on very steep or rocky terrain (Dakskobler et al., 2013).

The tree layer of ravine forests consists of characteristic broadleaf trees, which improve soil quality and provide high-value timber. Stand volume and site productivity vary depending on slope and altitude. The predominant tree species are sycamore maple (*Acer pseudoplatanus*), Norway maple (*Acer platanoides*), wych elm (*Ulmus glabra*), European ash (*Fraxinus excelsior*), large-leaved lime (*Tilia platyphyllos*) and small-leaved lime (*Tilia cordata*). In terms of floristic composition, these communities resemble beech forests classified into the Illyrian alliance of beech forests (*Aremonio-Fagion*) but are characterized by a higher abundance of hygrophilous and nitrophilous species. The understory is commonly comprised of mesophilous tall herbs and ferns with high requirements for nutrients, soil moisture, and air humidity, such as *Lunaria rediviva*, *Phyllitis scolopendrium*, *Polystichum setiferum* and *Urtica dioica*. Forests dominated by *Acer pseudoplatanus* occur on cooler and wetter sites, whereas *Tilia*-dominated forests, which are slightly more thermophilous, are found on warmer and drier sites (Dakskobler et al., 2013). In Slovenian ravine forests, *Tilia cordata* and *Tilia platyphyllos* frequently co-occur (Dakskobler et al., 2013; Kutnar et al., 2025). Additionally, *Tilia cordata* and *T. platyphyllos* can produce hybrids spontaneously when they coexist in proximity. These hybrids are known as *Tilia* × *europaea* (L.) (Maurer and Tabel, 1995).

2.2. Data description, preparation and analyses

In this study, we analyzed data from the first inventory cycle of the National Forest Inventory (2020–2024), collected and assessed on 3743 accessible sample plots. In Slovenia, national-level field forest data collection was conducted until 2018 on permanent sample plots as part of the Large-scale Monitoring of Forests and Forest Ecosystems (MFFE) system, using a systematic 4 × 4 km grid (Skudnik et al., 2021a; Skudnik et al., 2021b). The plots were measured in 2000, 2007, 2012, 2018, and 2024. In 2020, the MFFE inventory was supplemented and upgraded to become the National Forest Inventory (NFI) by the amendments of Slovenian Forest Act (1993) in 2025 (ZG, 1993). The NFI is conducted on an unaligned systematic sampling grid with a density of 2 × 2 km. Measurements on the same permanent sample plots are repeated every five years, and one inventory cycle lasts five years. The NFI is designed as a panel inventory system (Skudnik et al., 2023), with NFI plots divided into five panels. Within the NFI, data on the condition and changes in forests are collected annually on a panel, composed of permanent sampling plots on a representative grid with a density of 4 × 4 km, covering all of Slovenia. Approximately 750 sample plots are measured in the field each year. In total, the NFI consists of about 3750 sample plots throughout Slovenia (Pintar et al., 2024). Thus, the first NFI inventory cycle (2020–2024) was completed in 2024.

The NFI concentric permanent sample plot consists of four circular permanent subplots, each with a different radius and area (3.09 m with area 30 m^2, 7.98 m with area 200 m^2, 13.82 m with area 600 m^2 and 25.23 m with area 2000 m^2). On each of them, different variables or indicators are measured or assessed, as presented in the NFI manual (Skudnik et al., 2022). Living trees and shrubs with a diameter at breast height (DBH) of at least 10 cm were measured on circular plots with an area of 200 m^2, while individuals with a DBH of at least 30 cm were recorded on larger plots of 600 m^2. For each tree, azimuth and horizontal distance from the plot center were recorded. Regeneration and smaller living trees and shrubs were inventoried on circular subplots with an area of 30 m^2, located 10 m north of the center of each NFI permanent sample plot. On these subplots, all living tree and shrub individuals with a height of at least 1.3 m and a DBH of less than 10 cm were recorded (Skudnik et al., 2022).

All analyses were based exclusively on measurements within the NFI sample plot area, not on stand or compartment characteristics. According to the Slovenian NFI protocol, field crews record whether more than one developmental phase occurs within a plot. However, most analyzed plots contained only a single developmental phase. Plots where ravine forest species occurred only marginally within the plot area were excluded from the analysis to avoid bias in the calculated indicator values. This was implemented using a criterion based on the share of characteristic tree species, as explained in the following sections. The growing stock of trees and shrubs over the 10 cm DBH threshold in the NFI database is calculated using single parameter volume functions (tariffs) set out in Forest management plans for Forest management units and derived from the Slovenian Forest Service (SFS) compartments database (SFS, 2021). The volume of a tree or shrub is defined as the volume of the stem, including bark; that is, the volume of the trunk and all branches thicker than 7 cm. In contrast, the growing stock of regeneration and smaller living trees and shrubs is calculated based on measured DBH and tree height. The volume of regeneration and smaller living trees and shrubs is defined as the volume of the stem including bark. Mean values are reported with sampling errors, calculated using estimators for random sampling (Skudnik et al., 2023). Variables describing stand structure, canopy cover, and site conditions were recorded within a 2000 m^2 area and its immediate surroundings.

Different types of deadwood, including standing dead trees, lying dead trees, stumps, snags, and coarse woody debris, were also measured. Deadwood volume with a DBH (standing dead trees, lying dead trees) or diameter (stumps, snags, and coarse woody debris) of at least 10 cm were recorded on circular plots of 200 m^2, and those with a DBH or diameter of at least 30 cm on 2000 m^2 plots (Skudnik et al., 2022). The volume of standing and laying dead trees in the NFI database is calculated in the same way as the volume of living trees and shrubs above the 10 cm DBH threshold. The volume of coarse woody debris is calculated based on the mean diameter and length of each piece. For stumps and snags, the volume is calculated based on measurements of the mean diameter and height.

2.2.1. *Classification of ravine forests into homogeneous subtypes*

To identify Slovenian NFI permanent sample plots dominated by deciduous trees characteristic for ravine forests, we calculated the proportions of growing stock (m^3/ha) for the characteristic deciduous trees thicker than 10 cm, including sycamore maple (*Acer pseudoplatanus*), Norway maple (*Acer platanoides*), wych elm (*Ulmus glabra*), European ash (*Fraxinus excelsior*), large-leaved lime (*Tilia platyphyllos*) and small-leaved lime (*Tilia cordata*). Large-leaved lime and small-leaved lime were grouped together because of their ecological similarity and morphological characteristics, which make them sometimes difficult to distinguish reliably in the field. Characteristic ravine forest tree species were recorded on 1274 NFI plots. Of these, 467 plots contained more than 20% characteristic species in the growing stock, 299 plots more than 30%, and 212 plots more than 40%. For further analyses, we used only sample plots where the selected characteristic deciduous trees accounted for more than 50% of the growing stock and the total growing stock was at least 50 m^3/ha. The 50% threshold ensured that only plots dominated by characteristic deciduous trees were selected, while the 50 m^3/ha threshold excluded plots with only individual trees thicker than 10 cm. As a result, we obtained 153 plots from the total pool of 3743 NFI 2020–2025 plots and included them in further analyses. Plots dominated (>50%) by selected characteristic broadleaved tree species (sycamore maple, Norway maple, wych elm, European ash, large-leaved lime and small-leaved lime) were further interpreted as stands with a species composition corresponding to the ravine forests.

To ensure the analysis focused on stands where ravine forest characteristics are clearly expressed, only plots with at least 50% characteristic tree species and a growing stock of at least 50 m^3/ha were included. This threshold limited the dataset to developed stands in which typical ravine forest tree species form the dominant component of the tree layer. Similar proportions of characteristic species have been reported for reference ravine forest plots in Slovenia, where they account for more than 50% of the growing stock (Kutnar et al., 2025). Plots with lower shares of characteristic species likely represent transitional or mixed stand conditions in which ravine forest features are less pronounced. Similarly, stands with lower growing stock often correspond to earlier successional stages where the habitat type cannot yet be reliably identified. Systematic monitoring of these forests within the NFI began in 2020 using a 2 × 2 km grid. Therefore, the present analysis represents the first nationwide analysis based on currently available data. With the completion of future inventory cycles, additional plots – including currently harvested areas and young stands – will gradually become available for inclusion in further analyses after the next measurements. It can be assumed that very few new plots will be added, as these forests are managed in a close-to-nature manner, ensuring that most stands always contain some mature trees. This is especially characteristic of stands of minority forest habitat types, where mature trees intended for seed production often remain during stand regeneration. This is also confirmed by the fact that, according to this criterion, 4% of young stands were included in the analysis for *Acer*-dominated stands, 3% for *Fraxinus*-dominated stands, and 7% for *Tilia*-dominated stands. The subtypes of ravine forests were defined by objectively classifying sample plots based on their tree species composition. In the classification, we also included the most common tree species in Slovenian forests (each representing more than 5% of the Slovenian forests growing stock (Pintar et al., 2024)) that are also most frequently mixed with these ravine forests dominated by characteristic deciduous trees: European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*), silver fir (*Abies alba*), and sessile oak (*Quercus petraea*) as well as hornbeam (*Carpinus betulus*), hop-hornbeam (*Ostrya carpinifolia*), and field maple (*Acer campestre*) (Dakskobler et al., 2013). Because ravine forests occur in varying mixtures and with different degrees of admixture from other tree species, classification based solely on individual characteristic tree species or predetermined types would not capture the full diversity of stand structures (Pintar and Skudnik, 2024). Therefore, we used the unsupervised k-means clustering (UC, 2020) method for classification. This method identifies subtypes of ravine forests with similar species composition without prior assumptions regarding the number of subtypes. This approach is especially suitable when there is a continuous transition between different stand structures and the goal is to define ecologically meaningful types based on actual data. We included in the analysis the proportions of selected tree species (sycamore maple, Norway maple, wych elm, European ash, large-leaved lime and small-leaved lime, European beech, Norway spruce, silver fir, sessile oak, hornbeam, hop-hornbeam, and field maple) in the growing stock. We determined the number of clusters using the elbow method, which minimizes total variability within groups (Fig. 2) (UC, 2020). Mean growing stock was calculated at the plot level and then averaged across plots within each cluster (subtype). Tree species shares were calculated from these mean growing stock values (Fig. 3). We visualized differences among clusters (subtypes) using the NMDS method (Nonmetric Multidimensional Scaling) (Fig. 4). All statistical analyses were performed using the R 4.4.1 software environment (R Core Team, 2025).

For each compositional stand subtype, reference ranges and variability of structural, compositional, deadwood-related, and diversity indicators were summarized using descriptive statistics and boxplots. The indicators were chosen to reflect the main aspects of forest stand structure, composition, deadwood, and diversity relevant for characterizing stand-level biodiversity patterns, habitat assessment, and long-term monitoring (Table 1) (Borghi et al., 2024; Kutnar et al., 2025; Rybar et al., 2023; Smyčková et al., 2024).

Differences among subtypes were tested using univariate statistical tests. Before testing, data were checked for normality and homogeneity of variances using the Shapiro–Wilk and Levene tests. When both assumptions were satisfied, differences among groups were analyzed using one-way analysis of variance (ANOVA) with Tukey post hoc comparisons. If normality was met but variance homogeneity was violated, Welch's ANOVA was applied. When normality assumptions were not fulfilled, differences were assessed using the Kruskal–Wallis test. For pairwise comparisons, we then used Wilcoxon rank-sum tests with Bonferroni adjustment for multiple comparisons.

2.2.2. *Examination of ravine forest subtypes in relation to site-related, structural and compositional indicators*

After classifying the stand subtypes of ravine forests based on tree species composition and analyzing differences among subtypes using univariate statistical tests, conditional inference trees (Hothorn et al., 2006; Hothorn and Zeileis, 2015) were used to explore differences between the whole type and subtypes in terms of site-related characteristics, structural and compositional characteristics, and deadwood availability (Table 1). The conditional inference tree analysis integrated the results of the previous univariate analyses by identifying statistically supported thresholds in site-related, structural, and compositional variables that distinguish the three subtypes of ravine forests. While boxplots and corresponding statistical tests described the variability of individual stand attributes within clusters, the conditional inference trees analyzed how combinations of these attributes shape the distribution of forest stand types along ecological and structural gradients. Additionally, the analysis included a broader set of indicators than the descriptive assessment and statistical testing presented in the previous section (all indicators in Table 1). The set of indicators was adopted from the framework used by Kutnar et al. (2025) to assess forest stand structure and composition in a case study of forest habitat type *Tilio-Acerion* forests of slopes, screes, and ravines. We fitted conditional inference trees using the *ctree* function from the R package partykit (Hothorn et al., 2006; Hothorn and Zeileis, 2015). Inclusion of indicators for tree and tree complexity was constrained by a statistical significance level of 0.05 and a minimum node size of 20 plots.

2.2.3. *Analysis of the growing stock of regeneration and smaller living trees across ravine forest subtypes*

For each ravine forest subtype, we analyzed the proportions of tree species in the growing stock of regeneration and smaller living trees. Tree species accounting for more than 1% of the growing stock in at least one subtype were displayed. We then compared the proportions of the analyzed characteristic broadleaf species (sycamore maple, Norway maple, wych elm, European ash, large-leaved lime, and small-leaved lime) in the growing stock of regeneration and smaller living trees with their proportions in the growing stock of trees exceeding the 10 cm DBH threshold.

3. Results

3.1. *Classification of ravine forests into homogeneous subtypes*

In the k-means analysis, we determined that the optimal number of clusters (subtypes) was 3. This selection was based on a compromise between statistical criteria (elbow method) (UC, 2020) (Fig. 2) and

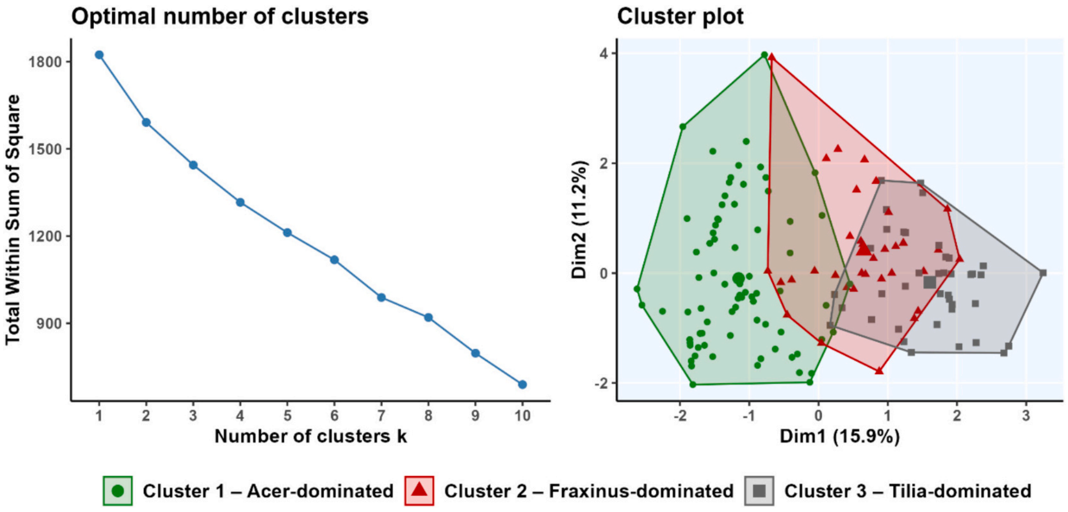

Fig. 2. Change in the total within-cluster sum of squares as a function of the number of clusters k (left), and classification of forest stand structural types into clusters (subtypes of ravine forests) using k-means across 153 selected NFI plots (right). Cluster 1 is dominated by *Acer pseudoplatanus*, cluster 2 by *Fraxinus excelsior*, and cluster 3 by *Tilia* spp.

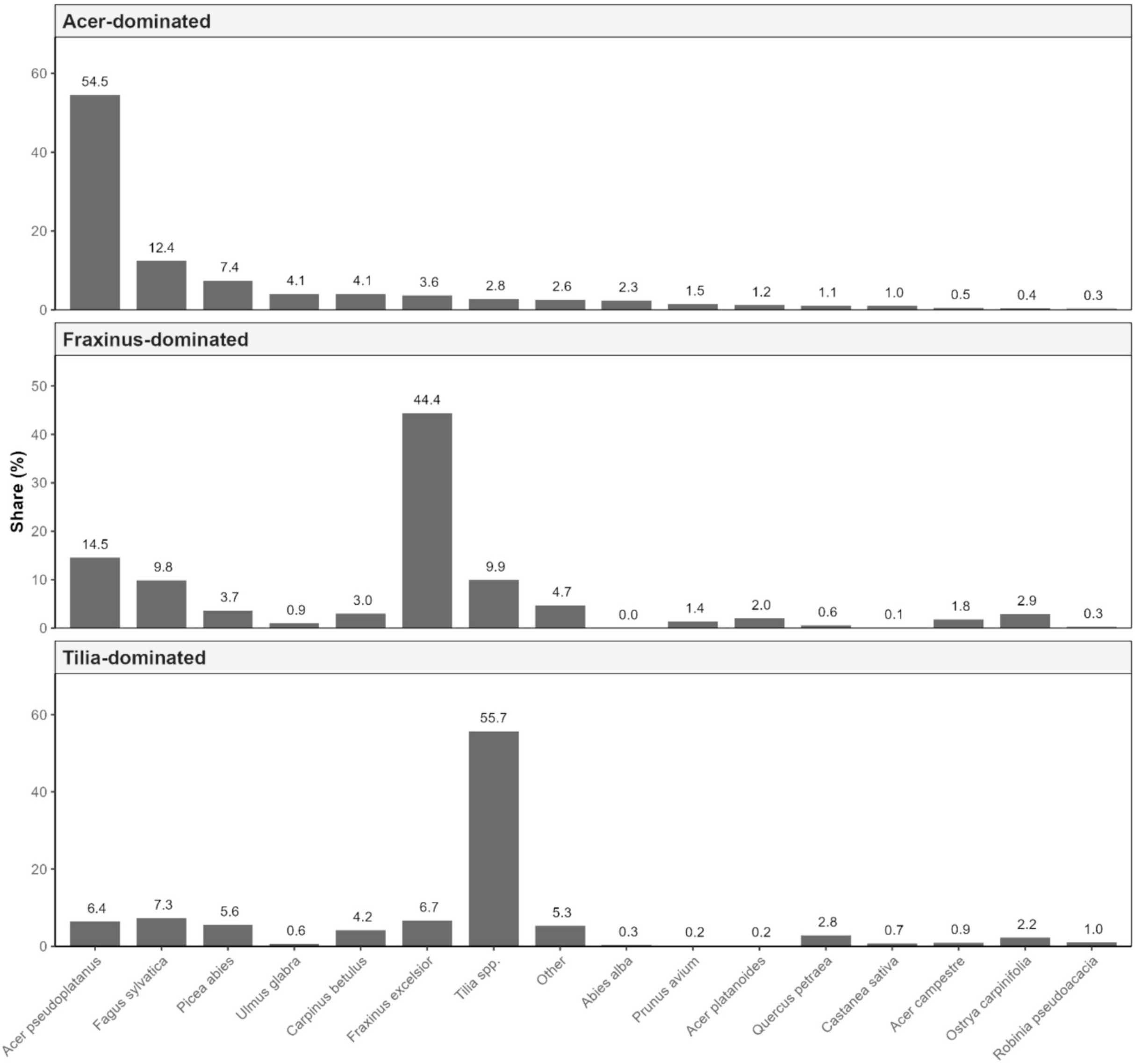

Fig. 3. Share of tree species in the growing stock in ravine forest subtypes.

ecological relevance (Kermavnar et al., 2023; Kutnar et al., 2025). Although higher numbers of clusters were further reduced within-cluster variance, these gains were marginal compared to the increased complexity and reduced interpretability of the resulting stand types. Identifying the optimal number of clusters using statistical methods (reducing the sum of squares within groups) and then confirming the number of groups based on plausibility and conceptual considerations was also presented by Hair et al. (2010).

A total of 77 plots were assigned to cluster 1, 35 to cluster 2, and 41 to cluster 3 (Fig. 5). The growing stock of living trees was 258.3 m^3/ha ± 17.0% in cluster 1, 242.1 m^3/ha ± 24.0% in cluster 2, and 282.1 m^3/ha ± 23.9% in cluster 3. The share of the dominant tree species in the growing stock was 54.5% for *Acer pseudoplatanus* in cluster 1, 44.4% for *Fraxinus excelsior* in cluster 2, and 55.7% for *Tilia* spp. in cluster 3 (Fig. 3). Accordingly, the individual subtypes of ravine forests were defined by the dominance of *Acer pseudoplatanus* (Cluster 1 – *Acer*-dominated), *Fraxinus excelsior* (Cluster 2 – *Fraxinus*-dominated), and *Tilia* spp. (Cluster 3 – *Tilia*-dominated). The proportion of *Tilia* spp., *Fraxinus excelsior* and *Acer pseudoplatanus* in the *Acer*-dominated subtype was 61.0%, in the *Fraxinus*-dominated subtype was 68.8% and in the *Tilia*-dominated subtype was 68.8%. The characteristic broadleaf species *Acer platanoides* and *Ulmus glabra* were present in all clusters, in each cluster comprising less than 4% of the growing stock. Their lowest proportions were observed in *Tilia*-dominated cluster 3, at 0.1% and 0.6%, respectively. *Fagus sylvatica* and *Picea abies* were most prevalent in the *Acer*-dominated cluster 1, accounting for 12.4% and 7.4% of the growing stock, respectively. In the other two clusters, the proportions of each species individually exceeded 3.0%.

Differences among clusters were visualized using the NMDS method (Fig. 4). The stress value was 0.2. The NMDS1 axis primarily reflects a decrease in the proportion of *Acer pseudoplatanus* and an increase in the proportion of *Tilia* spp., while the NMDS2 axis mainly represents an increase in the proportion of *Fagus sylvatica* and a decrease in the proportion of *Fraxinus excelsior*. Although the clusters formed relatively compact groups, the NMDS ordination revealed a continuous compositional gradient, with *Fraxinus*-dominated plots especially positioned between *Acer*-dominated plots and *Tilia*-dominated plots, indicating several cases of transitional stand composition.

More than 70% of the plots in the *Acer*- and *Tilia*-dominated subtypes and more than 80% of the plots in the *Fraxinus*-dominated subtype occured on the relief forms slope or convex and concave slope breaks (Fig. 6). In the *Acer*-dominated subtype, 12% of the plots occured on the relief form gully. The median and mean slope values were similar across all subtypes, ranging between 18 and 20° and 19–20° (Fig. 7). In the

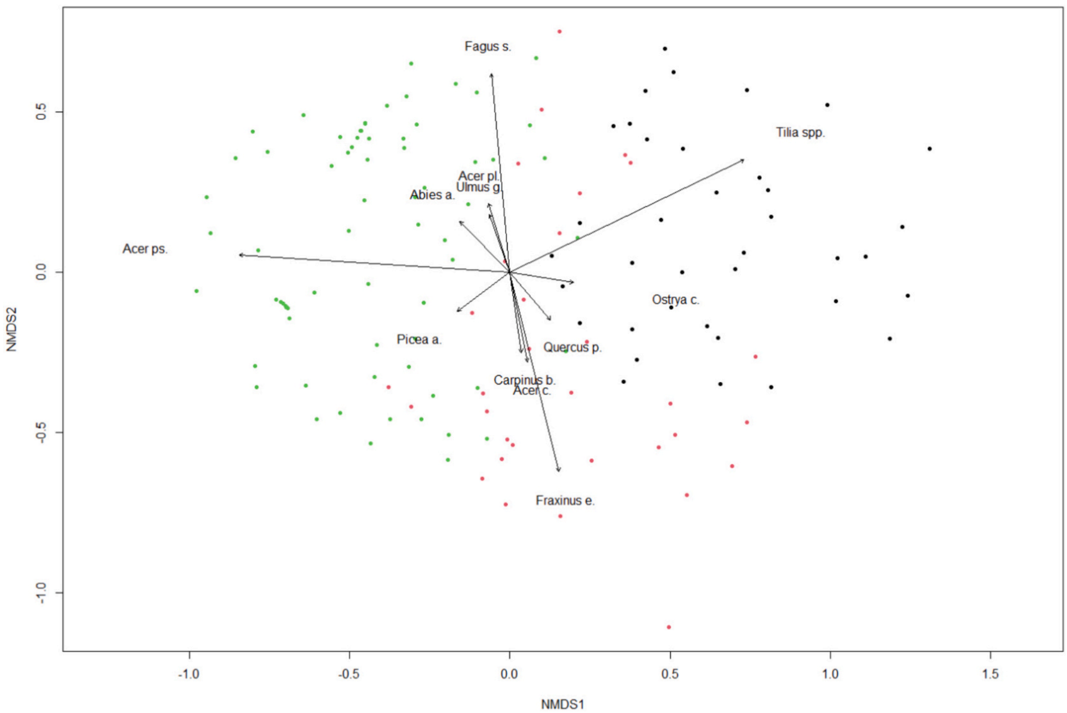

Fig. 4. NMDS analysis of tree species composition. Individual clusters/subtypes identified in the preliminary k-means analysis are marked: Cluster 1 (*Acer*-dominated plots) – green dots, Cluster 2 (*Fraxinus*-dominated plots) – red dots and cluster 3 (*Tilia*-dominated plots) – black dots. Arrows indicate passively fitted tree species vectors (envfit, $p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Acer-dominated subtype, slope ranged from 1 to 42°, in the *Fraxinus*-dominated subtype from 3 to 39°, and in the *Tilia*-dominated subtype from 1 to 45°.

The maximum DBH and the mean DBH of the five largest trees did not differ significantly among subtypes (one-way ANOVA, $p > 0.05$) (Fig. 8).

The number of trees per hectare differed significantly among subtypes (Kruskal–Wallis, $p < 0.001$) (Fig. 9). Post hoc comparisons revealed a significantly higher stand density in the *Tilia* spp. subtype compared to the *Acer*-dominated subtype, while the *Fraxinus*-dominated subtype showed intermediate values and did not differ significantly from either group. The density of large trees (DBH > 50 cm) did not differ significantly among subtypes (Kruskal-Wallis, $p > 0.05$). Stand density index (SDI) differed significantly among compositional clusters (one-way ANOVA, $p < 0.05$). SDI values are significantly lower in the *Acer*-dominated subtype compared to the *Tilia*-dominated subtype, while the *Fraxinus*-dominated subtype did not differ significantly from other subtypes.

Total growing stock did not differ significantly among subtypes (Kruskal–Wallis, $p > 0.05$) (Fig. 10). In contrast, the growing stock of the subtype-defining tree species (*Tilia* spp., *Fraxinus excelsior*, *Acer pseudoplatanus*) differed significantly among subtypes (Kruskal–Wallis, $p < 0.001$). *Tilia* spp. growing stock was significantly different among all three clusters ($p < 0.001$), with the highest values in the *Tilia*-dominated subtype, intermediate values in the *Acer*-dominated subtype, and the lowest values in the *Fraxinus*-dominated subtype. *Fraxinus excelsior* growing stock also differed significantly among subtypes ($p < 0.001$), with the *Fraxinus*-dominated subtype having higher growing stock than both the *Tilia*-dominated and *Acer*-dominated subtypes, which did not differ significantly from each other. Similarly, *Acer pseudoplatanus* growing stock was significantly different among subtypes ($p < 0.001$), with the highest growing stock in the *Acer*-dominated subtype, while the *Tilia* spp. and *Fraxinus*-dominated subtypes had comparably low values. The growing stock of major admixed species (*Fagus sylvatica* and *Picea abies*) was generally low compared to subtype-defining tree species and highly variable, which limited their suitability for robust statistical comparisons therefore they were evaluated descriptively. These tree species growing stock occur in all three subtypes, but the highest growing stock was found in the *Acer*-dominated subtype.

The Clark–Evans index showed significant differences among subtypes (Kruskal–Wallis, $p < 0.05$), with higher values in the *Acer*-dominated subtype than in the *Tilia*-dominated Subtype (Fig. 11). Species evenness also differed significantly among subtypes (one-way ANOVA, $p < 0.05$), with lower values in the *Acer*-dominated subtype compared to the *Fraxinus*-dominated subtype. In contrast, no significant differences were found for the Gini coefficient (one-way ANOVA, $p > 0.05$) or the dead-to-living volume ratio (Kruskal–Wallis, $p > 0.05$) among subtypes.

No significant differences among subtypes were detected for total deadwood volume, coarse woody debris, lying deadwood, or snags (Kruskal–Wallis tests, $p > 0.05$) (Fig. 12). In contrast, standing deadwood volume differed significantly among clusters (Kruskal–Wallis tests, $p < 0.05$), with higher values in the *Fraxinus*-dominated subtype compared to the other two subtypes. Stump volume also differed significantly among clusters (Kruskal–Wallis tests, $p < 0.01$). The *Acer*-dominated subtype had significantly higher stump volumes than the other two subtypes.

3.2. Examination of ravine forest subtypes in relation to site-related, structural and compositional indicators

When including multiple indicators from Table 1, none of the conditional inference trees were statistically significant at multiple variable levels. Therefore, we presented three decision trees below. Each tree included a statistically significant indicator for site conditions, forest structure, and composition. The other indicators were not statistically significant or were strongly correlated with those shown (for example, the Shannon Diversity Index of basal area heterogeneity for tree species was significantly correlated with Evenness), so they were not included in the analyses in this chapter. None of the deadwood indicators were statistically significant, so they were also not included in the analyses.

Table 1
Description of studied indicators related to forest structure, tree damages, deadwood biomass, and site conditions (Pintar et al., 2026).

Indicators	Description (*variables used to characterize reference ranges and variability of stand subtypes, the distributions or variability of other variables are presented in Appendix 1)
Slope	Angle between the ground surface under study and the apparent horizontal* (in °).
Altitude	Vertical distance of a point above mean sea level (m).
Aspect	Direction that a slope faces, expressed in degrees (0–360°) relative to north.
Heat load index (HLI)	Index that integrates slope and transformed aspect to approximate relative thermal conditions of a site (McCune and Keon, 2002).
Relief	Relief* is the predominant form of the earth's surface on which a plot lies (Skudnik et al., 2022). It is divided into seven categories: plain, ridge/hilltop, depression, slope, convex slope break, concave slope, gully.
Rockiness (Rock)	Rockiness is the proportion of the plot area that is covered by rocks (Skudnik et al., 2022). A rock is a free-lying or bedrock piece with a dimension of at least 30 × 30 × 30 cm.
Stoniness (Stone)	Stoniness is the proportion of the plot area that is covered by stones (Skudnik et al., 2022). A boulder is a free-lying piece of rock with a dimension of less than 30 × 30 × 30 cm.
Number of trees (N/ha)	Total number of the living trees and shrubs (Tot_N)*, number of large living trees (DBH higher than 50 cm) (L_Liv_T)* and number of trees in social position 1 (SP1_T), 2 (SP2_T), 3 (SP3_T), 4 (SP4_T) and 5 (SP5_T) (Borghi et al., 2024; Rybar et al., 2023).
Basal area (m^2/ha)	Total basal area of the living trees and shrubs (Rybar et al., 2023; Skudnik et al., 2021a).
Growing stock (m^3/ha)	Total growing stock of trees and shrubs (Tot_V)* (Pintar et al., 2024).
Maximum DBH (Max_DBH)	Maximum diameter at breast height (cm) of the trees* in the plot (Borghi et al., 2024; McElhinny et al., 2005).
Number of tree species (Tree_N)	Absolute number of tree species (Borghi et al., 2024; Pintar et al., 2024).
Mean DBH of 5 largest trees (DBH_5larg)	Mean diameter at breast height (cm) of 5 largest trees* (Smyčková et al., 2024).
Clark and Evans Aggregation Index (CE)	Clark and Evans Aggregation Index* was calculated as follows: $CE = \frac{r_A}{R_E}$- where $r_A = \frac{\sum_{i=1}^{n} HDist_{ij}}{n}$ and $r_E = \frac{1}{2}\sqrt{\frac{A}{N}}$ where $HDist_{ij}$ is the Euclidean distance between the i-th tree and its nearest neighbour and A is the plot area and N is the number of trees on the plot (Clark and Evans, 1954).
Gini coefficient (Gini)	Gini coefficient (0–1)* from frequencies in 5 cm DBH classes was calculated as follows: $GC = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}\left\|g_i - g_j\right\|}{2n^2 g}$ where gi is basal area in size class i (Gini, 1921).
Shannon Diversity Index	Shannon Diversity Index of basal area heterogeneity for tree species (SH_BAspec), 5 cm DBH classes (SH_BA5) and 10 cm DBH classes (SH_BA10): $H' = -\sum_{i=1}^{R} p_i \ln(p_i)\big)$ - where p_i is proportion of basal area of tree species or in 5 or 10 cm DBH classes (Shannon, 1948)(Pintar et al., 2024; Pintar and Hladnik, 2018).
Evenness Index (E)	Evenness Index* was calculated as follows: $E = \frac{SH}{\log_2 N}$, where SH is Shannon Diversity Index (SH_BAspec) and N is number of tree species (Magurran; 1988).
Stand density index (SDI)	Stand density index* was calculated as follows: $SDI = N \bullet (25/d_g)^{-1,605}$ - where N is number of trees (N/ha) and d_g is quadratic mean diameter (Pintar and Hladnik, 2018; Reineke, 1933).
Dead-to-living volume ratio (DLR)	Dead-to-living tree growing stock volume ratio* (Borghi et al., 2024).
Deadwood biomass (m^3/ha)	Total volume of deadwood biomass (DWD_V)*, volume of lying dead trees (LyingD_V)*, standing dead trees (StandD_V)*, stumps (Stump_V)*, snags (Snag_V)*, coarse woody debris (CWD_V)*, deadwood volume in decay class 1 (recently dead) (Dec1_DWD_V), 2 (early decay) (Dec1_DWD_V), 3 (moderate decay) (Dec3_DWD_V), and 4 (advanced decay) (advanced decay) (Borghi et al., 2024; Skudnik et al., 2021a).
Canopy closure	The stand canopy closure reflects the tree crown closure in the stand canopy (Skudnik et al., 2022).
Stand heterogeneity (Stand_het)	Stand heterogeneity is the proportion of the different layers of a stand. Stand layer composition describes the vertical structure of a forest (Skudnik et al., 2022).
Cover and form of tree layers	Cover of upper (Up_ lay _C), middle (Mid_ lay _C) and lower (Low_ lay _C) tree layer and form of upper (Up_ lay _F), middle (Mid_ lay _F) and lower (Low_lay _F) tree layer (Skudnik et al., 2022).
Vertical structure (Vert_str)	Form of the vertical structure or layering of a stand (Skudnik et al., 2022).
Development stage (Dev_Stage)	Development stage is the life stage of a stand defined by the predominant diameter of the trees in that stand (Skudnik et al., 2022).
Cover	Assessment of the horizontal stand structure or forest floor cover with all tree species present in all stand layers (Skudnik et al., 2022).

Most of the ravine forest plots were located at altitudes higher than 502 m (87 out of 153) (Fig. 13A). The conditional inference tree showed a statistically significant split by altitude ($p = 0.018$) at 502.12 m. This indicated a significant change in the distribution of the three compositional subtypes between the lower (≤ 502.12 m) and higher (> 502.12 m) altitude belts. The *Tilia*-dominated subtype was more common in the lower altitudinal belt, while the *Acer*-dominated was more prominent in the higher belt. The *Fraxinus*-dominated subtype was present in comparable proportions in both belts. The average altitude for the *Acer*-dominated subtype was 601 m (ranging from 209 m to 1496 m), for the *Fraxinus*-dominated subtype was 569 m (ranging from 182 m to 971 m), and for the *Tilia*-dominated subtype was 473 m (ranging from 191 m to 1045 m).

Most of the ravine forests were recorded in stands with higher stand density index (SDI) values (> 431.7; 98 out of 153) (Fig. 13B). The conditional inference tree showed a statistically significant split in SDI ($p = 0.006$) at a value of 431.7. The *Acer*-dominated subtype predominated in stands with lower SDI, while the *Tilia*-dominated subtype was relatively more common in stands with higher SDI. The *Fraxinus*-dominated subtype was represented in comparable proportions in both classes, without any marked dominance.

The conditional inference tree showed that Evenness was a statistically significant discriminating factor among subtypes ($p = 0.026$), with a cutoff value of 0.298 (Fig. 13C). In stands with lower Evenness values (Node 2; $n = 115$), the *Acer*-dominated subtype predominated, while in stands with higher Evenness index values, the *Fraxinus*-dominated subtype was more common.

3.3. Analyses of the proportion of growing stock in regeneration and smaller living trees

The growing stock of regeneration and smaller living trees was 14.6 m^3/ha ± 22.4% in the *Acer*-dominated subtype, 12.4 m^3/ha ± 14.7% in the *Fraxinus*-dominated subtype, and 15.6 m^3/ha ± 18.6% in the *Tilia*-dominated subtype. The sum of the proportion of *Acer pseudoplatanus*, *Fraxinus excelsior,* and *Tilia* spp. in the *Acer*-dominated subtype was 32.0%, in the *Fraxinus*-dominated subtype was 64.7% and in the *Tilia*-dominated subtype was 48.9% (Fig. 14). Of the non-characteristic deciduous trees, *Fagus sylvatica* was the most common in all subtypes, and in the *Acer*-dominated subtype it even ranked first with 30.7%. In the

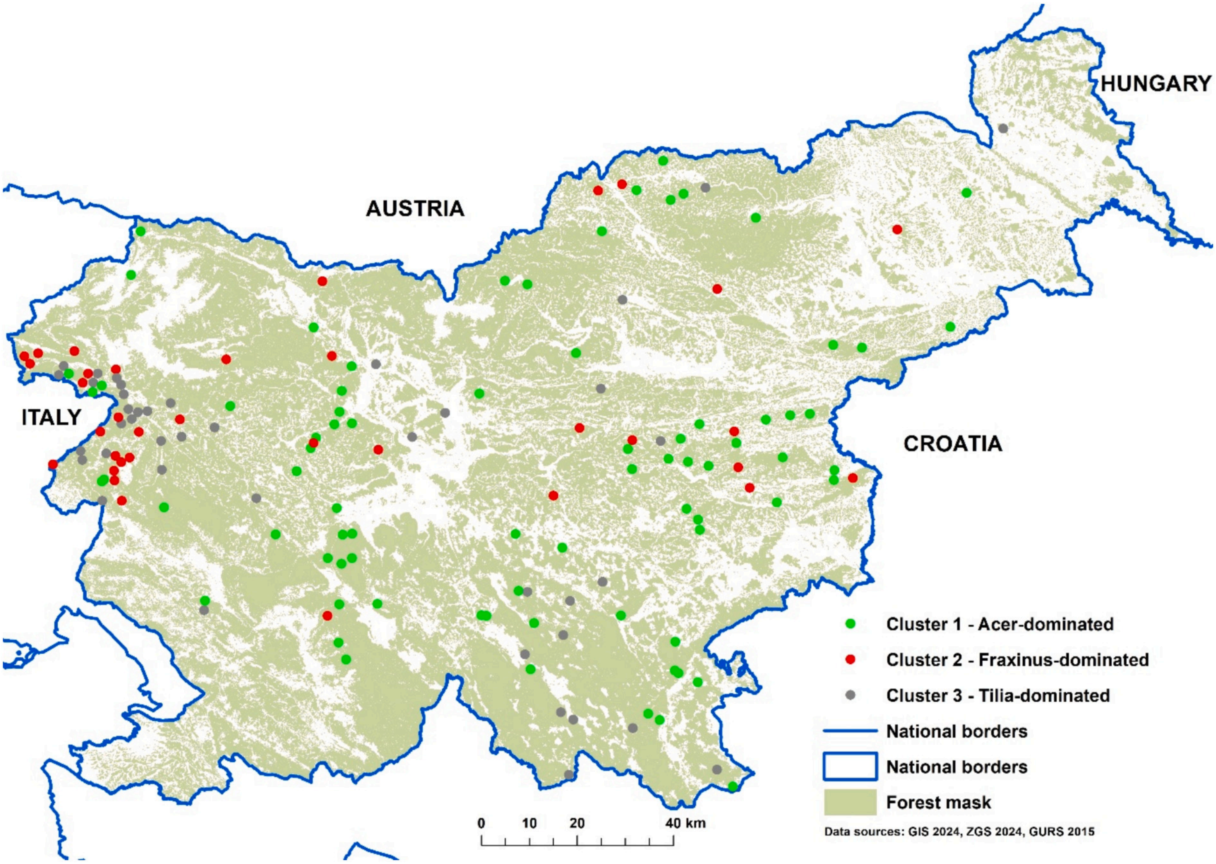

Fig. 5. Spatial distribution of NFI sample plots included in the analysis, classified into three ravine forest structural subtypes based on the dominant characteristic tree species across Slovenia.

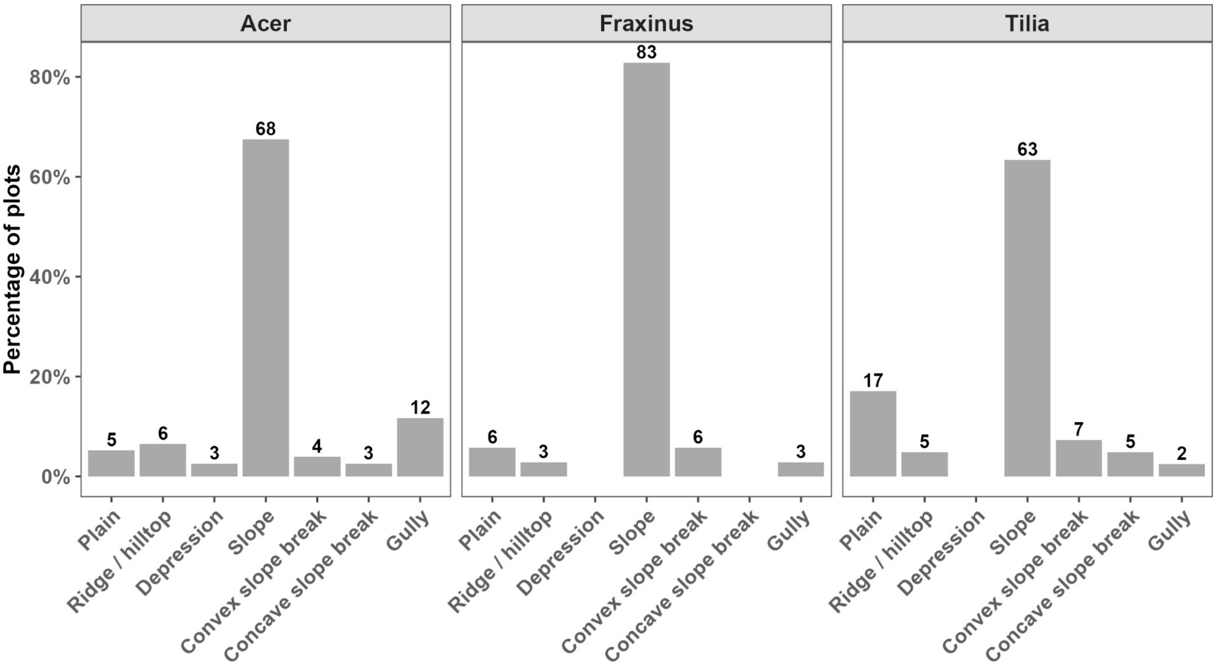

Fig. 6. Distribution of NFI sample plots across relief forms in each ravine forest subtype.

Tilia-dominated subtype, *Tilia* spp. was predominant with 29% in the growing stock of regenerating and smaller living trees.

4. Discussion

This study combined multivariate classification, univariate statistical

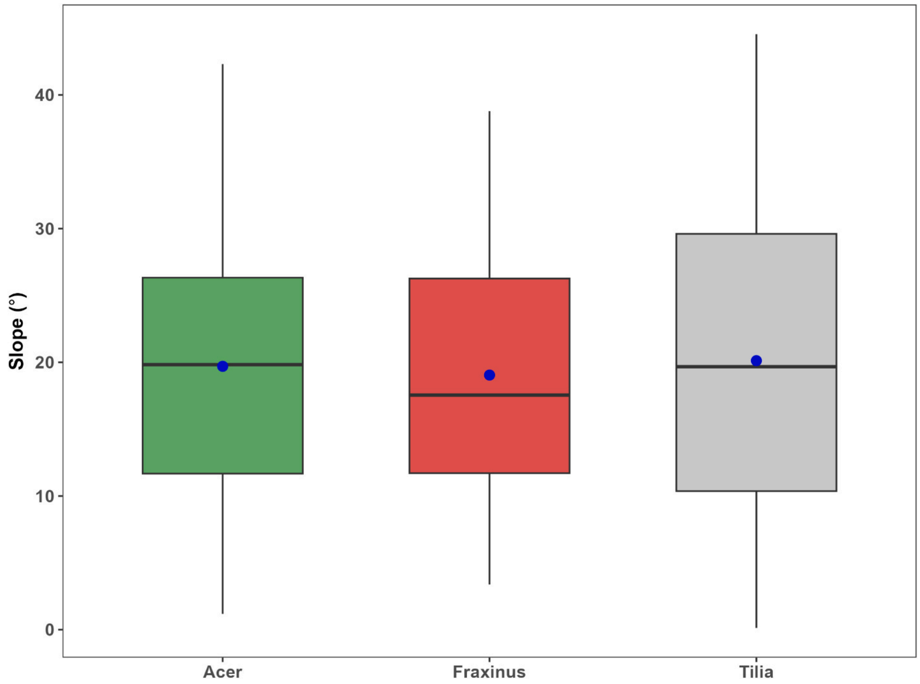

Fig. 7. Boxplots for slope across ravine forest subtypes. The boxplots display the median (horizontal line), the interquartile range (box; first and third quartiles), whiskers indicating values within 1.5 times the interquartile range (IQR). Blue points indicate the mean values.

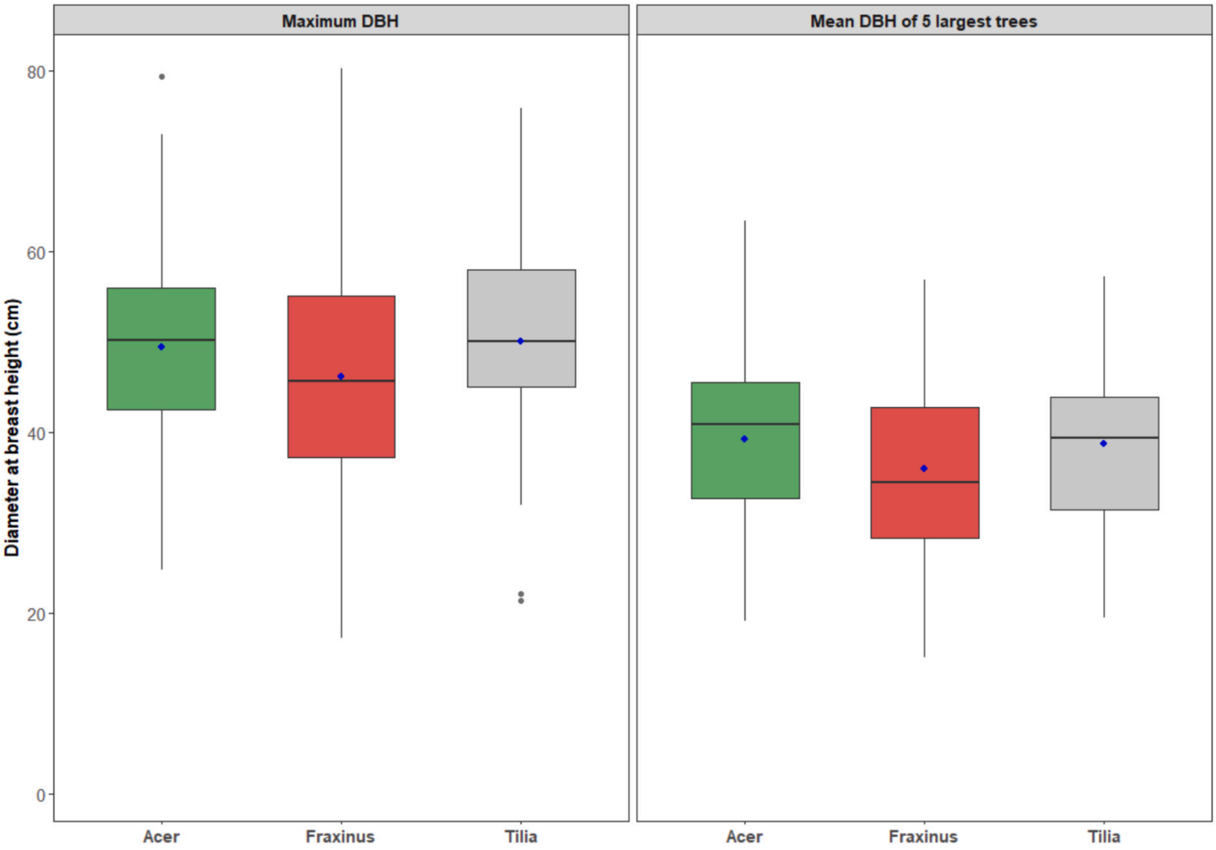

Fig. 8. Boxplots for total maximum DBH and mean DBH of 5 largest trees across ravine forest subtypes. The boxplots display the median (horizontal line), the interquartile range (box; first and third quartiles), whiskers indicating values within 1.5 times the interquartile range (IQR), and black dots representing outliers. Blue points indicate the mean values.

analyses, and integrative modeling to systematically characterize subtypes of the EU priority habitat type of ravine forests in close-to-

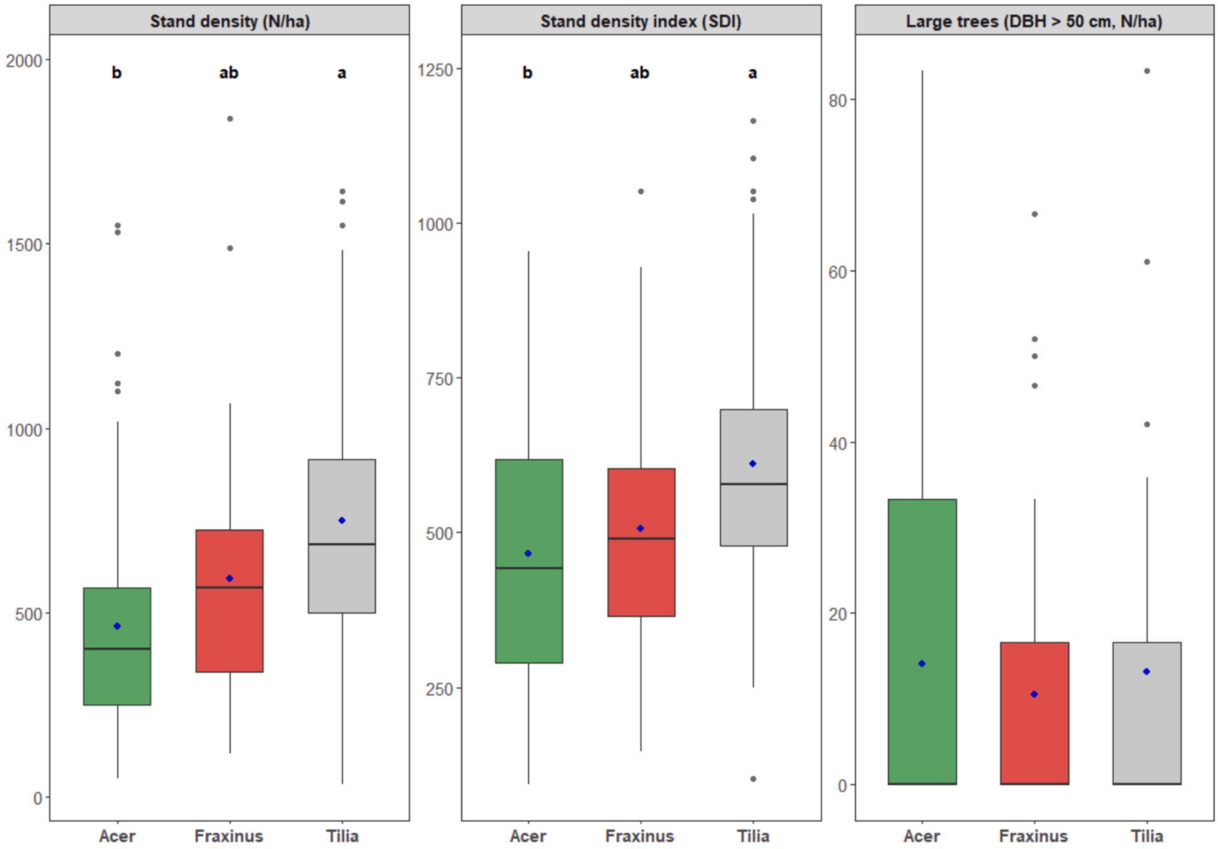

Fig. 9. Boxplots for total number of trees per hectare (stand density), stand density and number of large trees (> 50 cm) per hectare across ravine forest subtypes. The boxplots display the median (horizontal line), the interquartile range (box; first and third quartiles), whiskers indicating values within 1.5 times the interquartile range (IQR), and black dots representing outliers. Blue points indicate the mean values. Different letters above the boxplots indicate significant differences among subtypes within a panel based on post hoc multiple comparisons; groups that share a letter are not significantly different. Letters are shown only for indices with a significant overall test ($p < 0.05$).

nature managed forests. This is the first nationwide assessment of these forests in Slovenia, based on NFI data. In many areas mapped at the national level, data are often incomplete (Kermavnar et al., 2023; Kutnar et al., 2025), as are the reference values for state and conservation indicators (Kovac et al., 2018; Kovač et al., 2016). By first classifying stand types based on tree species composition and then examining their structural, ecological, and compositional indicators, the analysis provides a hierarchical and objective framework for interpreting variability within the studied forest habitat type. The indicators presented can serve as a foundation for determining the nationwide conservation status of this forest habitat type and for monitoring its conservation status in the future (EU, 2024).

Natural habitat identification requires a combination of criteria, including site conditions (e.g. slope, soil and geomorphology), understorey vegetation and structural indicators. However, the applied approach allows the identification of stands with a clear dominance of characteristic broadleaf species at the national scale using NFI data. In this study, we present the classification of the current condition of ravine forests on a systematic sampling grid, where measurements began in 2020 and will be repeated at regular five-year intervals. After remeasuring all plots, which is currently underway, we will also be able to analyze changes in condition and the direction in which the development of this habitat type is heading, as the tree layer is crucial for assessing the conservation status of forest habitat types (Kovac et al., 2020; Tinya et al., 2021). Unlike traditional phytosociological approaches that often rely on potentially biased selection, NFI provides a spatially systematic representation of forest stands across the entire country. As an EU priority habitat type, ravine forests were studied in plots where characteristic deciduous trees accounted for more than 50% of the growing stock and the total growing stock was at least 50 m^3/ha. In this context, it is possible that the analysis also included individual plots where the succession phase of characteristic deciduous trees is occurring, such as in beech communities (Dakskobler et al., 2013). However, the predominance of targeted characteristic deciduous trees may also be observed in some climax forest communities, which are characterized by a similar stand structure to that of ravine forests. Therefore, with the aim to improve method used in this study; we propose that future research supplement with additional phytosociological surveys and soil analyses on these plots. In this context, the NFI was primarily used as a tool for the initial detection of plots where such forests may occur, which has not yet been conducted at the national level. The selected plots could then be further verified through field assessments by phytosociology experts and detailed soil analyses. Tree species composition was used as the primary criterion because it is the most reliable and consistently recorded variable available in the Slovenian NFI plots, while detailed site conditions and plant community indicators are not systematically recorded. This variable can be linked to the identification of ravine forests, whose distribution and structural characteristics remain insufficiently documented at the national scale. The selected characteristic tree species and the applied ≥50% growing stock threshold are supported by observations from reference plots in the Boč-Haloze-Donačka Gora study area, where detailed dendrometric measurements and phytosociological surveys were conducted (Kutnar et al., 2025). On these reference plots, the classification species used in this study accounted for more than 50% of the growing stock. The mean growing stock of these forests was reported as 437 m^3/ha (Kutnar et al., 2025), which is higher than the mean values observed in the three compositional subtypes identified in this study (242–282 m^3/ha). This

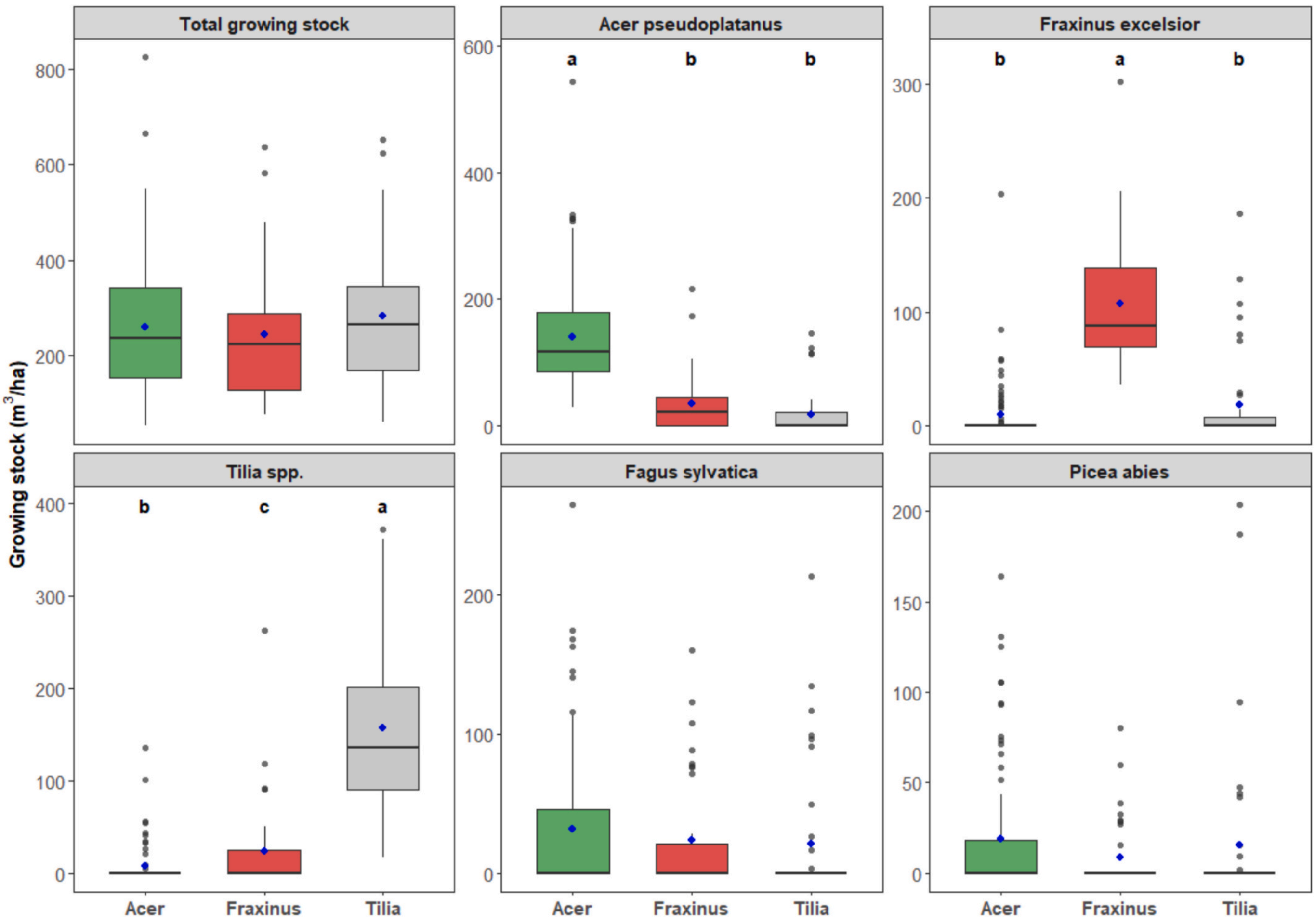

Fig. 10. Boxplots for total growing stock and species-specific growing stock (for the tree species defining each cluster and for the two most frequently admixed species) across ravine forest subtypes. The boxplots display the median (horizontal line), the interquartile range (box; first and third quartiles), whiskers indicating values within 1.5 times the interquartile range (IQR), and black dots representing outliers. Blue points indicate the mean values. Different letters above the boxplots indicate significant differences among subtypes within a panel based on post hoc multiple comparisons; groups that share a letter are not significantly different. Letters are shown only for indices with a significant overall test ($p < 0.05$).

difference may reflect the predominance of older stands in the Boč-Haloze-Donačka Gora area.

The classification based on tree species composition and the ≥50% growing stock threshold of characteristic species is also supported by relief forms. Most analyzed plots across all compositional subtypes are found on slopes, slope breaks, gullies, ridges, and depressions. This pattern indicates that stands selected by tree species composition are associated with the typical topographic conditions of the ravine forests (Baran et al., 2018; Baran et al., 2020; Kermavnar et al., 2023; Kutnar et al., 2025). This systematic sampling design enables a quantitative and reproducible characterization of structural and compositional variability within Natura 2000 forest habitat types. Moreover, because comparable NFI frameworks are implemented in many European countries, the indicator-based approach presented here is transferable and allows cross-national comparisons and harmonized monitoring of habitat conditions. NFI-based analyses complement expert-driven classical phytosociological description by providing empirically reference ranges and statistically supported thresholds of indicators suitable for long-term monitoring. This could also supplement and improve the six-yearly national reporting under Article 17 of the Habitats Directive (Habitats Directive, 1992). In particular, it could supplement the assessments of conservation indicators for this and other forest habitat types. The identified subtypes were represented by 35 to 77 plots within a systematic 2 × 2 km NFI sampling grid, a range that approaches or exceeds the commonly suggested lower threshold for obtaining robust estimates in large-scale forest inventories (Tomppo et al., 2010). Although sampling uncertainty was expected to be higher in cluster 2, which had 35 plots, the sampling density was sufficient to support meaningful differentiation of structural and compositional patterns among subtypes. This is further supported by the fact that clusters were classified based on minimal compositional variability within groups.

Stump volume was recorded on 70 of the 153 analyzed plots and may indicate recent or past harvesting activity. Although the *Acer*-dominated subtype had significantly higher stump volumes than the other two subtypes, the overall mean values were low (4 m^3/ha), suggesting generally moderate harvesting intensity across the analyzed stands. This suggests that harvesting has likely not substantially altered the main structural characteristics of the stands. In Slovenia, most forests are managed according to close-to-nature silvicultural principles aimed at maintaining continuous forest cover, promoting natural regeneration, and preserving structural heterogeneity and species composition (Diaci, 2021; Kutnar et al., 2023). Under such management regimes, harvesting interventions are typically moderate and maintain uneven stand structures comparable to those found in many natural forest communities. This combination of natural site conditions and long-term close-to-nature forest management should also be considered when interpreting structural indicators used in the assessment and long-term monitoring of ravine forests (habitat type 9180*) under the Natura 2000 framework.

Based on tree composition, which is a basic component in forest habitat types, we identified three subtypes of ravine forests, dominated

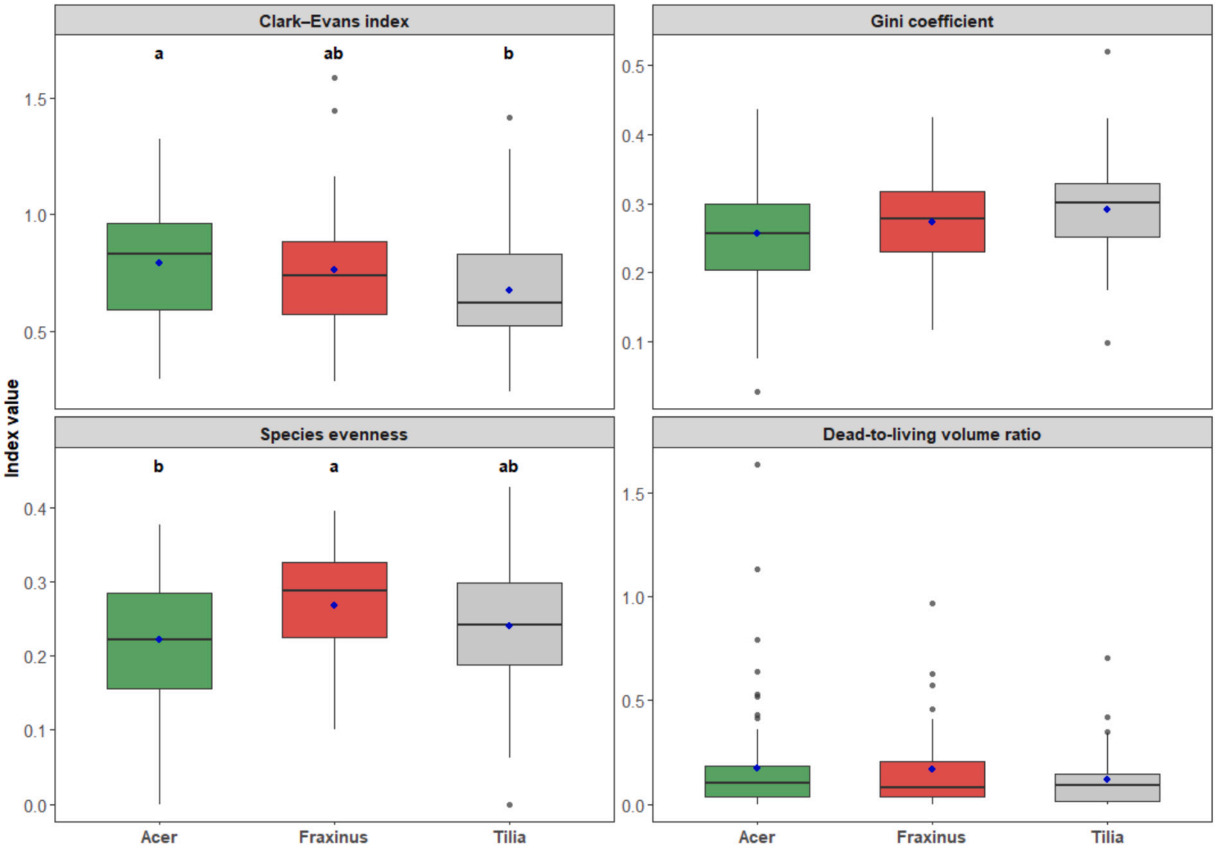

Fig. 11. Boxplots for spatial, structural and compositional indices across ravine forest subtypes. Panels show the Clark–Evans index, Gini coefficient, species evenness, and the dead-to-living volume ratio (DLVR). The boxplots display the median (horizontal line), the interquartile range (box; first and third quartiles), whiskers indicating values within 1.5 times the interquartile range (IQR), and black dots representing outliers. Blue points indicate the mean values. Different letters above the boxplots indicate significant differences among subtypes within a panel based on post hoc multiple comparisons; groups that share a letter are not significantly different. Letters are shown only for indices with a significant overall test ($p < 0.05$).

by *Acer pseudoplatanus*, *Fraxinus excelsior*, and *Tilia* spp. Similarly, in a case study of the Boč-Haloze-Donačka gora area, covering 10,882 ha in eastern Slovenia, ravine forests were classified by dividing the *Acer*-dominated stands into two further subtypes: *Acer pseudoplatanus*–*Ulmus glabra* stands, and *Acer pseudoplatanus* stands occurring on more acidic soils with an admixture of *Castanea sativa* (Kermavnar et al., 2023; Kutnar et al., 2025). At the national level in Slovenia, due to the very low presence of *Castanea sativa*, it was more appropriate to classify only one subtype of *Acer pseudoplatanus* forests. In this subtype, the proportion of trees thicker than 10 cm in the growing stock was 4% for *Ulmus glabra* and 1% for *Castanea sativa*.

In all subtypes, we detected a significant proportion of *Fagus sylvatica* and *Picea abies* in the growing stock of trees thicker than 10 cm. The largest proportion was found in the *Acer*-dominated subtype (12% and 7%). The largest proportion of *Fagus sylvatica* in the *Acer*-dominated subtype indicates that ravine forests, especially the *Acer*-dominated subtype, are most commonly found within a belt (matrix) of various *Fagus sylvatica* forests with relatively similar site and ecological conditions. Due to certain similarities and transitions between them, the *Aceri-Fagetum* forest association was also described (Dakskobler, 2008; Kutnar et al., 2012). Using different methodological approach and database, Kutnar et al. (2011) found a very high proportion of *Picea abies* (around 40%) in *Tilio-Acerion* forests of slopes, screes, and ravines (HT 9180*). This proportion was considerably higher than in our case, even in the subtype with the highest proportion of *Picea abies* (*Acer*-dominated subtype – 7%). In the past (after World War II), in Slovenia, *Picea abies* was often planted on sites dominated by *Acer pseudoplatanus*, which are very productive. Recently, a decrease in the proportion of *Picea abies* growing stock in Slovenia has been observed due to the effects of climate change and natural disturbances (Kutnar et al., 2021; Pintar et al., 2024), which also explains the decrease in *Picea abies* growing stock in ravine forests.

Although ravine forests are an azonal forest habitat type, we found a statistically significant higher occurrence of the *Tilia*-dominated subtype at lower altitudes, below 502 m. Similarly, the occurrence of *Tilia*-dominated stands at lower altitudes (below 600 m) has also been observed in the Carpathians (Pach et al., 2013), while the occurrence of *Acer pseudoplatanus* stands was found at altitudes above 1100 m, the majority occur at lower altitudes. In our study, the highest stand of *Acer*-dominated subtype was recorded at 1496 m.

In the *Tilia*-dominated subtype, compared to the *Acer*-dominated, we found a statistically higher number of trees per hectare and a higher SDI, as well as a statistically significantly lower Clark and Evans Index. We explain this by the larger crown areas and growing space of *Acer pseudoplatanus* at the same diameter compared to *Tilia* spp. (Hemery et al., 2005). The greater growing space and higher light requirements of *Acer pseudoplatanus* (Hemery et al., 2005) and thus its greater dominance in stands, can also be explained by the fact that the *Acer pseudoplatanus* subtype predominates in stands with a lower Evenness value (below 0.3). Hemery et al. (2005) also found that the number of trees per hectare in fully occupied stands with no crown overlap (at an average diameter of 60 cm) was 90 for *Acer pseudoplatanus* compared to 153 for *Tilia* spp. Similarly, *Tilia* spp. mostly grow in clusters, which was also confirmed by the statistically significant lower Clark and Evans index in *Tilia*-dominated stands (0.68) compared with *Acer*-dominated stands (0.79). A lower index was also found in *Tilia*-dominated stands (0.64) compared to other stands (0.81) of ravine forests in a case study of the Boč-Haloze-Donačka gora area (Kutnar et al., 2026). The Evenness index

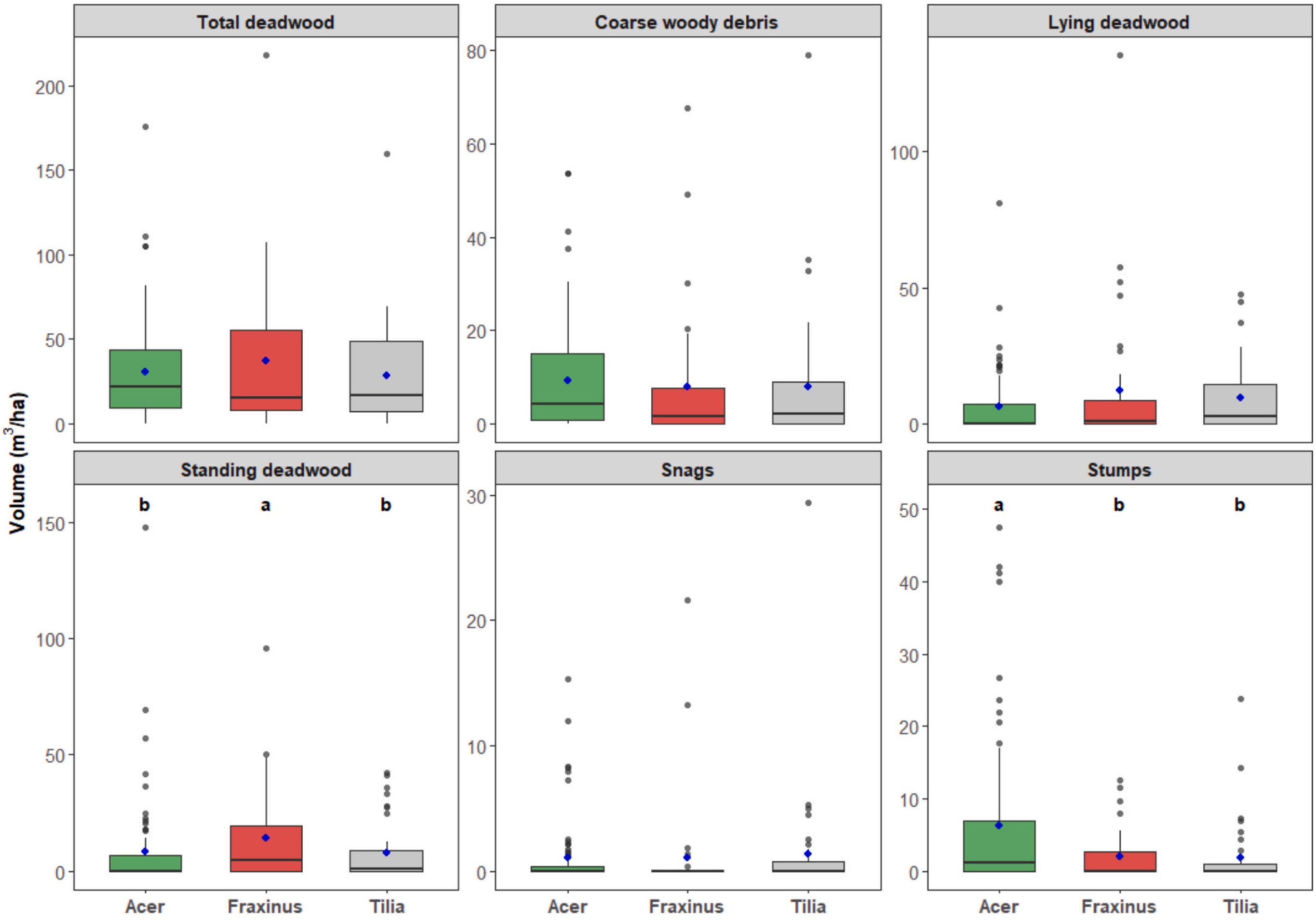

Fig. 12. Boxplots for total deadwood volume and individual deadwood components volume (coarse woody debris, lying deadwood, standing deadwood, snags, and stumps) across ravine forest subtypes. The boxplots display the median (horizontal line), the interquartile range (box; first and third quartiles), whiskers indicating values within 1.5 times the interquartile range (IQR), and black dots representing outliers. Blue points indicate the mean values. Different letters above the boxplots indicate significant differences among subtypes within a panel based on post hoc multiple comparisons; groups that share a letter are not significantly different. Letters are shown only for indices with a significant overall test ($p < 0.05$).

was particularly affected by the criteria used to select plots. By focusing on plots where characteristic ravine forest tree species made up more than 50% of the growing stock, the analysis highlighted stands where these species dominated the tree layer. Including plots with lower proportions of characteristic species would likely introduce additional species typical of surrounding forests, which could increase the calculated evenness values.

We did not detect any statistically significant differences between the maximum DBH and mean DBH of the five largest trees among the individual subtypes. The average maximum DBH observed in our study (46–50 cm) was slightly lower than the mean maximum DBH reported for selected managed *Tilio-Acerion* forests in southern Poland (60.7 cm) (Baran et al., 2020), but it remained within the same upper diameter size class. The *Acer*-dominated subtype was closest to the number of trees per hectare in selected *Tilio-Acerion* forests in southern Poland, with 463 compared to 477 (Baran et al., 2020). The other two subtypes had slightly higher values: 592 for *Fraxinus*-dominated and 749 for *Tilia*-dominated. We also found a slightly lower number of large trees per hectare in *Tilia*-dominated subtype (13) and Acer-dominated subtype (14) in our case, compared to 23 in selected stands in southern Poland (Baran et al., 2020). The smaller number of large trees in the managed forests was compensated by higher tree density, which was also observed in managed forests in southern Poland (Baran et al., 2020). The number of large trees was even lower in the *Fraxinus*-dominated subtype (10), which was a result of the high mortality rate of large trees caused by the invasive alien fungal disease ash dieback (*Chalara fraxinea*), which has recently spread widely in Slovenian forests (Ogris et al., 2009).

In the *Fraxinus*-dominated subtype, the volume of standing dead trees was statistically significantly higher than in the other two subtypes (14 m^3/ha compared to 8 m^3/ha). This was also higher than the volume of standing dead trees in Slovenian forests, which was 8 m^3/ha (Kušar and Neumann, 2024). According to the Rules on the Protection of Forests (Pravilnik o varstvu gozdov, 2009), at least 3% of the deadwood volume must remain in Slovenian forests relative to the total growing stock. Deadwood volume should be distributed as evenly as possible and include all thickness classes, especially those over 30 cm. The required amount of deadwood volume by type, such as standing deadwood, is not specified. We also attribute the higher amount of standing deadwood observed in the *Fraxinus*-dominated subtype to the high mortality rate of trees caused by ash dieback. Ash dieback and the much smaller proportion of *Fraxinus excelsior* in the growing stock of regeneration and smaller living trees compared to growing stock of trees over the 10 cm DBH threshold indicate a significant reduction in the growing stock of *Fraxinus excelsior* in this subtype and, consequently, a deterioration in the longterm existence of ravine forests status of this subtype.

In the other two subtypes, there was also a decrease in the proportion of dominant tree species (*Tilia* spp. and *Acer pseudoplatanus*) in the growing stock of regeneration and smaller living trees compared to the growing stock of overstory trees. In all three subtypes, *Fagus sylvatica*,

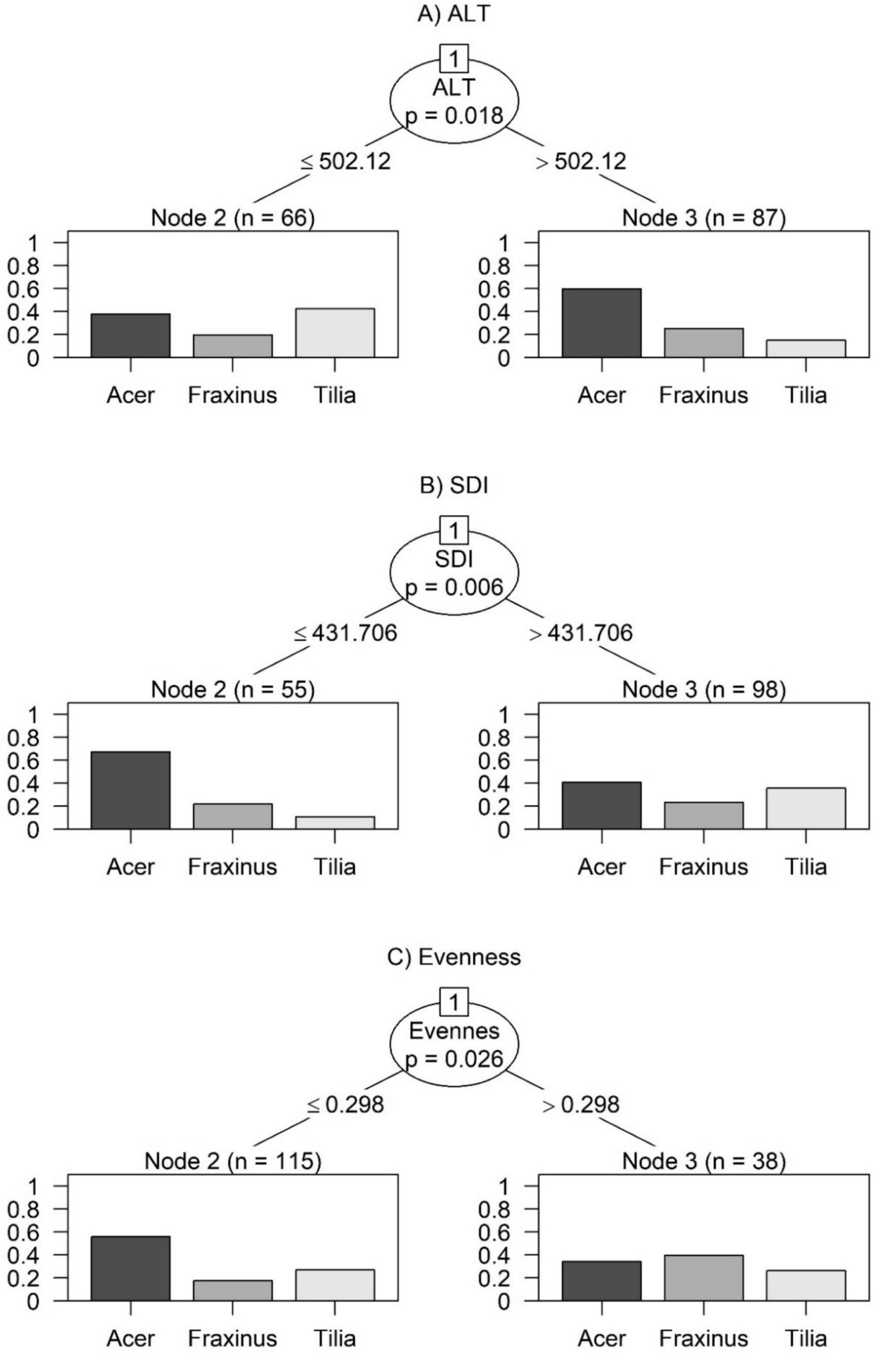

Fig. 13. Conditional inference trees for altitude (ALT), stand density index (SDI), and species evenness. Terminal nodes show the relative frequencies of the three *ravine* forest subtypes within each node, with node size (n) representing the number of sample plots.

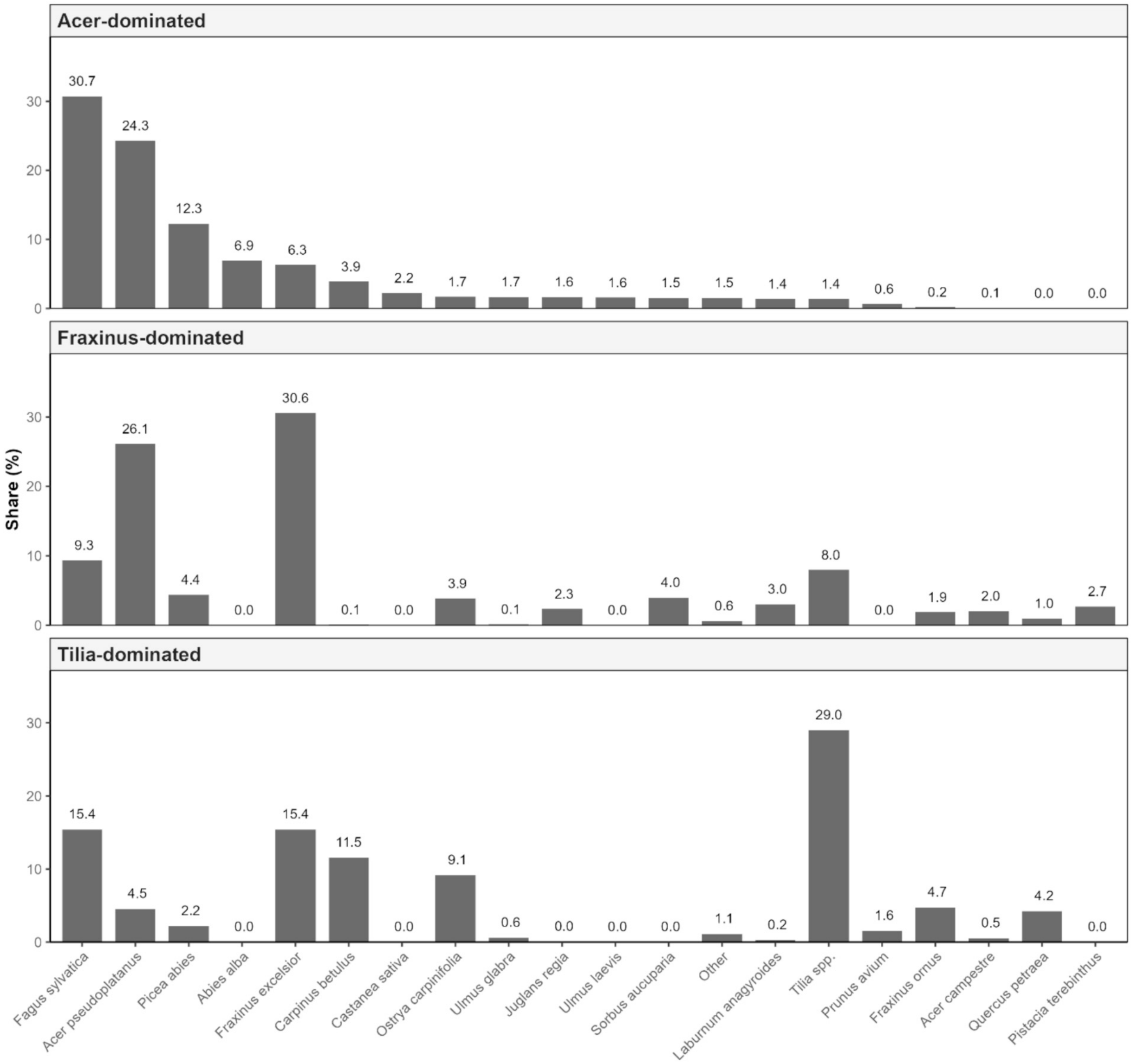

Fig. 14. Share of tree species in the growing stock of regeneration and smaller living trees in each ravine forest subtype.

which is a more shade-tolerant tree species compared to the characteristic tree species, had the highest proportion in the growing stock of regeneration and smaller living trees. In the *Acer pseudoplatanus* subtype, it was even the dominant tree species with 31%. *Fagus sylvatica*, like in the *Acer*-dominated subtype, also dominated the growing stock of regeneration and smaller living trees in Slovenian forests with 32% (Pintar et al., 2024), in forests where beech dominated the growing stock of adult trees with 32%. The third most abundant species in the *Acer*-dominated subtype in the growing stock of regeneration and smaller living trees was *Picea abies* (12%), which ranked second in Slovenian forests with 14%. The second most abundant species in this subtype was *Acer pseudoplatanus* (24.3%), whereas in Slovenian forests it ranked seventh with 3% (Pintar et al., 2024). In all three subtypes of ravine forests, we observed a lack of natural regeneration of key tree species, which is crucial for maintaining the long-term existence of ravine forests. A lack of regeneration in the ravine forests in eastern Slovenia has already been noted (Kermavnar et al., 2023; Kutnar et al., 2025).

The use of descriptive boxplots and univariate tests quantifies the current range of key structural attributes. This is particularly relevant for ravine forests and other Natura 2000 forest habitat types, where clearly defined reference values for indicators are often lacking and challenges such as low precision for rare or small-area habitats exist (Alberdi et al., 2019). Conditional inference trees further complement these analyses by identifying statistically supported thresholds in environmental, structural, and compositional variables, offering an integrative perspective on how site conditions, stand structure and composition, and deadwood volume differentiate the identified stand subtypes. In the future, it will be possible to monitor changes in the conservation status of this habitat type based on repeated measurements of NFI plots, which are conducted in Slovenia (Pintar et al., 2024) and in 11 European countries at five-year intervals (Gschwantner et al., 2016). The observed ranges of structural and compositional attributes, deadwood components, and diversity indices provide empirical reference conditions that reflect the current nationwide variability of ravine forests.

5. Conclusions

The structural and compositional variability observed in NFI data within characteristic broadleaf-dominated ravine forests should be recognized as an inherent feature of these Natura 2000 habitat types, rather than as a deviation from target conditions. Natural habitat identification requires a combination of criteria, including site conditions (such as slope, soil, and geomorphology), understorey vegetation, and structural indicators. However, the applied approach enables the identification of stands with a clear dominance of characteristic broadleaf species at the national scale using NFI data. The selection criteria used ($\geq$50% share of characteristic species and $\geq$ 50 m^3/ha growing stock) ensured that the analysis focused on well-developed stands in which ravine forest characteristics are clearly expressed. The distinction of compositional subtypes captureed the natural variability within this heterogeneous habitat type. The results of this study showed that such variability occured across different compositional subtypes (*Acer*-, *Fraxinus*-, and *Tilia*-dominated) and was reflected in several indicators describing stand structure, deadwood volume, diversity indices, and regeneration patterns. The *Tilia*-dominated subtype was more common in the lower altitudinal belt ($\leq$ 502 m), while the *Acer*-dominated subtype was more prominent in the higher belt ($>$ 502 m). The *Acer*-dominated subtype predominated in stands with SDI lower than 432, while the *Tilia*-dominated subtype was relatively more common in stands with higher SDI. In stands with Evenness values lower than 0.3, the *Acer*-dominated subtype predominated, while in stands with higher Evenness index values, the *Fraxinus*-dominated subtype was more common. Empirical reference ranges derived from these indicators can support habitat assessments by situating individual stands within the observed spectrum of conditions.

This approach is particularly relevant because NFI plots are distributed on a systematic sampling grid, and measurements are repeated at five-year intervals. In future studies, integrating structural indicators from NFI data with phytosociological and soil surveys could improve monitoring frameworks for Natura 2000 forest habitat types and help detect potential shifts in tree species dominance and stand dynamics over time, especially since the distribution and structural characteristics of these habitats remain insufficiently documented at the national scale.

CRediT authorship contribution statement

Anže Martin Pintar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Janez Kermavnar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luka Krajnc:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gal Kušar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lado Kutnar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2026.114841.

Data availability

The data used in this study are available on Digital repository of Slovenian research organizations at https://doi.org/10.20315/Data.0017.

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