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Structural and compositional indicators of the conservation status of forest habitats: A case study of ravine forests – EU priority habitat type *Tilio-Acerion*

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ABSTRACT

Maintaining the conservation status of habitat types such as the ravine forests (*Tilio-Acerion*) assessed in this study is a priority of the European Natura 2000 network. Ravine forests often occur in smaller, fragmented areas, but are widely distributed throughout European forests. Reliable indicators of the conservation status of Natura 2000 habitats, which support monitoring and reporting under Article 17 of the Habitats Directive, are often not available. Therefore, we tested a set of 161 structural and compositional variables as potential indicators of the conservation status of close-to-nature managed ravine forests in a Natura 2000 site in eastern Slovenia. The studied forests ranged from *Acer pseudoplatanus*-dominated stands to those dominated by *Fraxinus excelsior* or *Tilia* species. Most forests were classified as having either a favourable or inadequate conservation status. The main pressures included game browsing and mortality of the key tree species, primarily caused by invasive alien fungi. Favourable conservation status was associated with less intensively managed *Tilia*-dominated stands on rocky ridges and steep slopes. It was also linked to higher tree layer cover, particularly of *Acer pseudoplatanus*, in well-preserved forest stands. Conversely, indicators of bad conservation status were associated with *Fraxinus excelsior*-dominated stands that had been severely affected by invasive alien fungi, resulting in increased volumes of standing and lying deadwood. The resulting tree mortality created more open stand canopies with increased light availability at the forest floor, as indicated by the higher number of plant species in the herb and shrub layer. The conservation status of ravine forests is likely to be increasingly threatened by the adverse effects of climate change, including pests and disease outbreaks and other disturbances. To ensure the continued favourable conservation status of ravine forests, it is essential to monitor key indicators and apply appropriate forest management measures.

1. Introduction

Natura 2000 represents an integrated framework for the identification, maintenance and protection of sites with high biodiversity value (Velázquez et al., 2010; Kovač et al., 2018). The Natura 2000 network serves as a pivotal instrument for mitigating biodiversity loss in Europe (Ricci et al., 2024).

One of the most effective methods for conserving biodiversity is to maintain habitats in a favourable conservation status (Cantarello and Newton, 2008). Achieving this crucial but often challenging goal requires considerable monitoring efforts. The initial step in this process involves identifying the specific location of a given habitat type. Such data form the basis for all subsequent assessments and actions related to its conservation status. Evaluating the conservation status of habitats of EU interest is fundamental to maintaining them in favourable condition (Velázquez et al., 2010). To achieve a favourable conservation status of Natura 2000 habitats (Habitats Directive, 1992; Kovač et al., 2018), it is essential to make an overall assessment of habitat quality from a nature conservation perspective.

Indicators of the conservation status of forest habitats that directly support forest biodiversity in a broader sense have historically received less research attention (Kovač et al., 2020). Over the past two decades, research has increasingly focused on defining appropriate terminology and identifying suitable indicators for assessing the conservation status

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of forest habitat types (Ellmauer and Essl, 2005; Cantarello and Newton, 2008; Kovač et al., 2016), as well as on data collection methods (Winter et al., 2008) and evaluation approaches (Kovač et al., 2016; Kovac and Grošelj, 2018; Tsiripidis et al., 2018). In the context of biodiversity research, biodiversity indicators are considered appropriate measures to assess key components of biodiversity in forest ecosystems, including forest habitat types, species habitats and species themselves (Larsson et al., 2001; Kovač et al., 2020).

The legal basis for evaluating the conservation status of habitat types of EU interest is the Habitats Directive (1992). Article 11 of the Habitats Directive (1992) requires Member States to monitor the habitats and species listed in its annexes (with habitats in Annex I), while Article 17 requires a report to be submitted to the European Commission every six years in a standardized format. The core of the Article 17 report is an assessment of the conservation status of the habitats and species covered by the Habitats Directive (1992). This assessment is based on information regarding the current status and trends of species populations or habitats, as well as the main pressures and threats affecting them.

Before assessing forest habitats, it is essential to first identify all forest sites to provide valid estimates of habitat types or even habitat subtypes (Kovač et al., 2016; Kermavnar et al., 2023a). Assessing forest habitats across large areas is a complex task, particularly when the target habitat exhibits strong natural heterogeneity. Such heterogeneity may arise from variations in species composition and environmental conditions across different ecological gradients. A habitat type is defined as a vegetation system characterized by specific ecological, structural and floristic features, with a specific species composition that provides a living environment for a wide range of organisms. The structure and composition of forest stands and vegetation play a crucial role in shaping the conservation status of forest habitats (Tinya et al., 2021). Vegetation and stand characteristics such as tree species composition and age distribution directly influence biodiversity and different groups of organisms, as different species thrive in different types of forest vegetation and stands. Maintaining varied forest structures and compositions supports diverse flora and fauna and contributes to important ecosystem services. The quality and conservation status of forest habitats are often associated with stand density, species diversity and composition, and the presence of old trees and deadwood (Tinya et al., 2021).

Forest vegetation and stand characteristics, together with ecological characteristics, are also central to identifying forest habitat areas, assessing their current conservation status and indicators, and determining long-term conservation measures, particularly in small-scale ravine forests. These forests belong to the alliance *Tilio platyphylli-Acerion pseudoplatani* (short: *Tilio-Acerion*) and are listed as a European priority forest habitat type, *Tilio-Acerion* forests of slopes, screes and ravines (Natura 2000 habitat code 9180*) (EC, 2013). Their distribution is widespread across the mountainous regions of temperate Europe (EEA, 2025), ranging from Boreal to Northern Europe (EC, 2013; Paal, 2009), through Central Europe (EC, 2013; Zukal et al., 2020), to the Iberian Peninsula (Crespo et al., 2008; Campos et al., 2011), Southeastern Europe (Košir et al., 2008; Kraradžić et al., 2020) and Eastern Europe (Hrivnák et al., 2010; Baran et al., 2018, 2020). This habitat type has been recorded in 21 EU Member States and identified in 2323 designated Natura 2000 sites across Europe (EEA, 2025). Notably, a considerable number of Natura sites containing habitat type 9180* are found in Germany (753 sites), France (294), Italy (222), Slovakia (133), Sweden (120), the Czech Republic (108) and Spain (102) (EEA, 2025).

These forests occur in erosional gullies, ravines, canyons, cliffs, steep rocky slopes and rock outcrops. From an ecological and forest stand perspective, they can be divided into two distinct groups. The first is characterised by wetter and cooler sites, dominated by sycamore maple (*Acer pseudoplatanus*), classified within the *Lunario-Acerenion* sub-alliance. The second comprises drier and warmer sites dominated by limes (*Tilia platyphyllos* and *T. cordata*) and thermophilous broadleaves (EC, 2013; Steinacker et al., 2019), classified within the *Tilio-Acerenion* sub-alliance.

At the European scale, *Tilio-Acerion* forests represent an understudied and data-poor habitat type. Most studies have applied vegetation-based and traditional phytosociological methods (Hrivnák et al., 2010; Kraradžić et al., 2020; Zukal et al., 2020). However, research on their conservation status and structural and compositional indicators remains relatively scattered (Baran et al., 2018; 2020). According to Baran et al. (2018), low-intensity forest management in ravine forests may resemble natural disturbance regimes, to which these communities are well adapted. The authors called for further research of biodiversity, particularly with regard to forest structural indicators. Their subsequent study confirmed that stand structure responds more strongly to management interventions than species composition (Baran et al., 2020). A comprehensive set of indicators capturing various aspects of forest structure and composition is therefore needed to assess the impacts of forest management on biodiversity and other potential factors influencing the conservation status of forest habitat types (Simonson et al., 2013; Kovač et al., 2020).

In Slovenia, preliminary studies of ravine forests have revealed major gaps in data on their spatial distribution, structural characteristics and indicators of conservation status (Kutnar et al., 2011; Kermavnar et al., 2023a). The limited availability of detailed maps and accurate spatial and field data hampers reliable conservation status assessment (Kutnar and Dakskobler, 2014). This highlights the need for improved knowledge of this habitat through systematic fieldwork and targeted surveys. To illustrate the structure and conservation status of habitat type 9180*, we present a case study from the Boč-Haloze-Donačka gora Natura 2000 site in Slovenia. The site is notable for its relatively high representation of the target habitat type. However, the conservation status of its natural structure and functions has been less well documented, primarily due to the limited data and the habitat's occurrence in small, often remote patches with varied topography.

Based on preliminary field mapping of *Tilio-Acerion* forests in the selected Natura 2000 site (Kermavnar et al., 2023a), a representative set of sites in close-to-nature managed forests was selected with the aim of assessing forest structure and composition and identifying indicators relevant to the conservation status of this habitat type. This study had two main aims: i) to assess the extent to which identified pressures affect the conservation status of ravine forests designated as the *Tilio-Acerion* priority EU habitat type, and ii) to evaluate site and vegetation characteristics, as well as tree and stand characteristics, in order to identify the key structural and compositional indicators that determine the conservation status of the selected *Tilio-Acerion* forests.

2. Materials and methods

2.1. Study area

The study area is located in a forested landscape in eastern Slovenia (46.294°N, 15.734°E; see Fig. 1). The site is designated within the Natura 2000 network as Boč-Haloze-Donačka gora (site code SI3000118; hereafter referred to as the BHD site). The BHD site provides habitat for 15 species included in the Natura 2000 list, comprising invertebrates, mammals, amphibians and flowering plants. It also provides protection for seven habitat types designated under the Habitats Directive (EEA, 2022a).

The total area of the BHD site is 10,882 ha, of which 853 ha are forest zones (nature conservation units) assigned to priority habitat type of *Tilio-Acerion* forests (9180*). The elevation ranges from 240 m (in the Dravinja Valley) to 978 m (at the summit of Boč Mountain). The site exhibits diverse relief and geological conditions, resulting in a mosaic of forest vegetation types. The dominant forest habitats are Illyrian beech forests (91K0) and *Luzulo-Fagetum* beech forests (9110). *Tilio-Acerion* forests account for 1.3 % of the forest stands within the BHD site (Babij et al., 2020). While structural characteristics such as a sufficient share of standing or lying deadwood are generally favourable, there is a lack of younger developmental stages, despite the frequent occurrence of noble

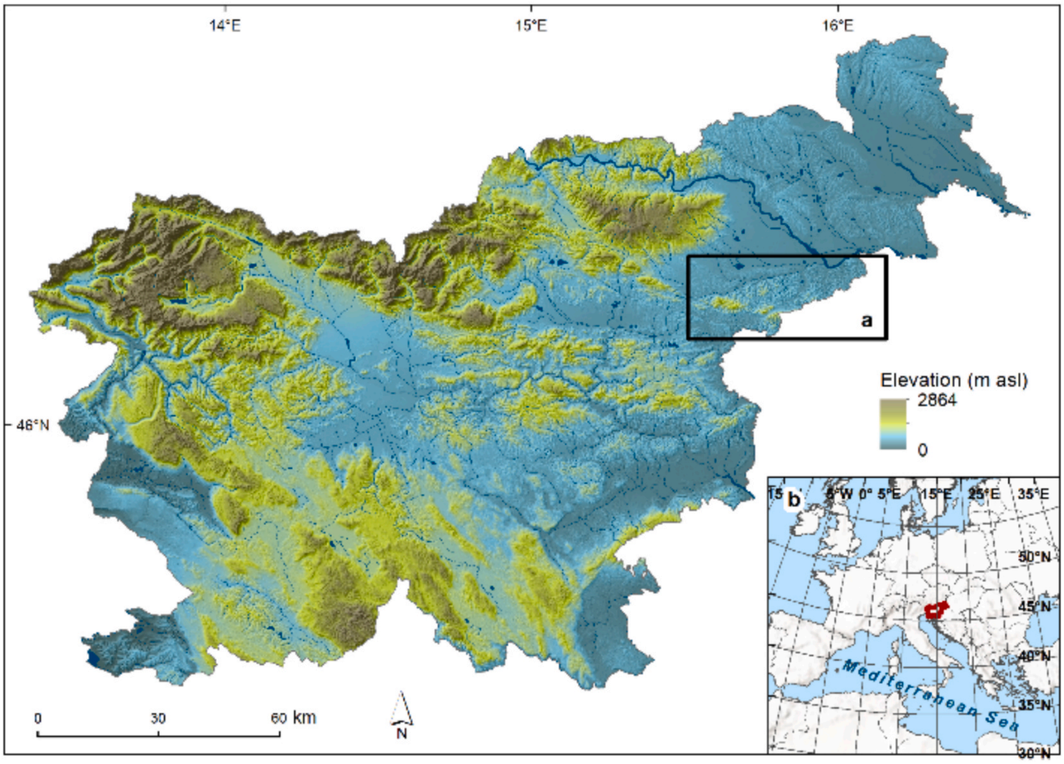

Fig. 1. Location of the Boč-Haloze-Donačka gora (Natura 2000 site) study area in the eastern part (Sub-Pannonian region) of Slovenia (a) and the location of Slovenia in Europe (b).

broadleaves as pioneer species on primarily beech sites (Babij et al., 2020).

The northern slopes of the mountain are steeper than the southern slopes, with more than half of the surface area having slopes greater than 20°. The predominant topographic features include peaks, ridges, slopes and small plains. Due to the predominance of carbonate bedrock, the area lacks a developed surface river network, as water quickly percolates into the karst subsurface. This geological and topographical diversity is reflected in the area's varied of soil types. Brown calcareous soils, rendzinas and rankers occur in an alternating pattern depending on slope and parent material. Pseudogleys are the dominant geological feature on the slopes of the Haloze hills and Donačka gora (both located in the eastern part of BHD), while deep soils on clayey and silty deposits are predominant in the valleys (Karlo and Senegačnik, 2020).

The climate is Sub-Pannonian, with the majority of precipitation occurring in spring and summer, and with a drier winter season. Boč Mountain, with its higher elevation and rugged relief, experiences a harsher climate than that found in the surrounding hills and valleys. Annual precipitation on Boč averages around 1200 mm. During the growing season, mean temperatures are approximately 15 °C in the Haloze hills and around 8 °C at the summit of Boč. The area's soil and climatic heterogeneity support floristic elements from the Mediterranean, Central European, Alpine, Illyrian and steppe regions (Karlo and Senegačnik, 2020).

2.2. Description of the forest habitat type

Slovenia has the highest proportion of Natura 2000 sites among all EU member states (almost 38 % of the country's terrestrial area (EEA, 2024)). Ravine forests of the habitat type *Tilio-Acerion* forests of slopes, screes and ravines (9180*) face significant challenges in the context of biodiversity conservation. According to Slovenia Forest Service data (SFS, 2024), these forests cover less than 0.5 % of Slovenia's forest area and typically occur in small patches, often in stony or rocky gullies, dolines, ravines, torrential fans, gravelly slopes, moist rock formations or sun-exposed ridges at altitudes ranging from the colline to the altimontane vegetation belt (Dakskobler et al., 2013). Soils in these forests are primarily colluvial-deluvial, with rare occurrences of rendzinas and brown calcareous soils. Dystric brown soils and ranker or eutric brown soils have been documented in some cases. Litter decomposition is relatively rapid, resulting in high nutrient availability. Some stands are found on very steep or rocky terrain (Dakskobler et al., 2013).

The tree layer is composed of so-called noble broadleaves, which improve soil quality and provide high-value timber. The most dominant plant 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 but have a greater abundance of hygrophilous and nitrophilous species. The understory typically includes mesophilous tall forbs and ferns with high requirements for nutrients, soil moisture and air humidity, such as *Lunaria rediviva*, *Phyllitis scolopendrium*, *Polystichum setiferum* and *Urtica dioica*. *Acer pseudoplatanus* forests dominate on colder and wetter sites, while slightly more thermophilous *Tilia* forests are found on warmer, drier sites (Dakskobler et al., 2013). In this part of Europe, the phytogeographic differentiation of these forest plant communities from those in Central Europe is reinforced by the presence of some relict and endemic Illyrian species that survived the Quaternary glaciations in southern European refugia. These include typical forest herbs such as *Lamium orvala*, *Stellaria montana*, *Cardamine waldsteinii* and *Scopolia carniolica* (Košir et al. 2008).

According to the EUNIS habitat classification (Chytrý et al., 2020; EEA, 2022b), these forests are classified as Illyrian ravine forests. In Slovenia, *Tilio-Acerion* forests occur across a wide range of site and stand conditions, spanning a broad ecological amplitude and a wide array of forest associations. Based on the established forest communities (associations), the classification described in the Typology of Forest Sites in Slovenia (Kutnar et al., 2012) and the updated phytosociological publications (Dakskobler et al., 2013; Bončina et al., 2021), the studied habitat type 9180* is heterogenous and even subtypes have been established (Kermavnar et al., 2023a).

These stands have high nature conservation value, often providing habitat for rare and protected species (Kutnar and Dakskobler, 2014). However, due to their small size and fragmented occurrence, they are more vulnerable to threats than larger forest types. Key pressures include climate change, fragmentation and overexploitation (Dakskobler et al., 2013; Kutnar and Dakskobler, 2014). Due to the lack of accurate field mapping of *Tilio-Acerion* stands in the past, data on the location and quality of current Natura 2000 sites are inadequate. Consequently, the conservation status of *Tilio-Acerion* forests (9180*) in Slovenia was evaluated as unfavourable (Kutnar et al., 2011) and even declining, according to the most recent Natura 2000 report (EIONET, 2013–2018).

2.3. Data collection

In accordance with the provisions set out in the Habitats Directive (1992), a natural habitat is considered to have a favourable conservation status when the following conditions are met:

1. Its natural range and the area it covers within that range are stable or increasing;
2. The specific structure and functions necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future; and.
3. The conservation status of its typical species is favourable.

The extent and condition of the *Tilio-Acerion forest* habitat type (ravine forests), referenced in the first line of the text above, was previously examined in a preliminary study (Kermavnar et al., 2023a). In that study, close-to-nature managed ravine forests designated as *Tilio-Acerion* forests were mapped in the BHD Natura 2000 site, and the conservation status of the habitat in all mapped polygons was evaluated. Based on the Habitats Directive (1992) – Article 17 reporting process, each polygon was assigned one of three conservation status categories: favourable, inadequate (or unfavourable) or bad (or poor).

To identify indicators associated with the structure and functions of the habitat type and its typical species according to the Habitats Directive (1992) (see lines 2 and 3 above), a set of 81 study plots was selected within the mapped polygons of the ravine forests in the BHD site. All study plots were circular and covered an area of 2000 m^2 (with a radius of 25.23 m). Within these study plots, smaller circular subplots were installed, all with the same centre point. The area and radius of these subplots varied according to the methodology used and the specific parameters set (see Canullo et al., 2016; Skudnik et al., 2022; Pintar et al., 2024). Vegetation and site characteristics were assessed in 400 m^2 subplots (Canullo et al., 2016), while forest stand structure and tree characteristics were assessed in subplots ranging from 200 to 2000 m^2 (Skudnik et al., 2022; Pintar et al., 2024). Habitat pressures and overall conservation status were evaluated at the scale of the entire 2000 m^2 circular plot.

The plot selection process ensured a representative spread across the three mapped conservation status classes (favourable, inadequate, bad) and captured as much ecological and geographical variation within the *Tilio-Acerion* forest habitat type as possible (Kermavnar et al., 2023a). Stratified sampling was applied based on the area proportion of each conservation status class. Plot distribution within each class was balanced as evenly as possible according to the geographical and ecological characteristics across the BHD site. In total, 23 plots were selected from polygons assessed as favourable (Fig. 2), 46 plots from those with an inadequate (unfavourable) status, and 12 plots from those with bad (poor) conservation status (Fig. 3).

Understanding pressures and threats provides insight into the main drivers affecting habitat conservation status and can help identify appropriate restoration actions (EEA, 2023a). According to the Article 17 reporting guidelines (EEA, 2023a), "pressures" are factors that have acted during the current reporting period, while "threats" are those expected to act during the next two reporting periods (i.e. over the next 12 years). Some factors may be classified as both if their impact is ongoing and expected to continue (EEA, 2023a). At both local and polygon scales, the main pressures and threats to the studied ravine forests in the BHD site were documented in Kermavnar et al. (2023a). Drawing on that study, a broader European context (EEA, 2023a, 2025) and previous detailed assessments (Babij et al., 2020; Karlo and Senegačnik, 2020; SFS, 2019, 2022a, 2022b; Kermavnar et al., 2023a), the following pressures were identified and evaluated at the plot level:

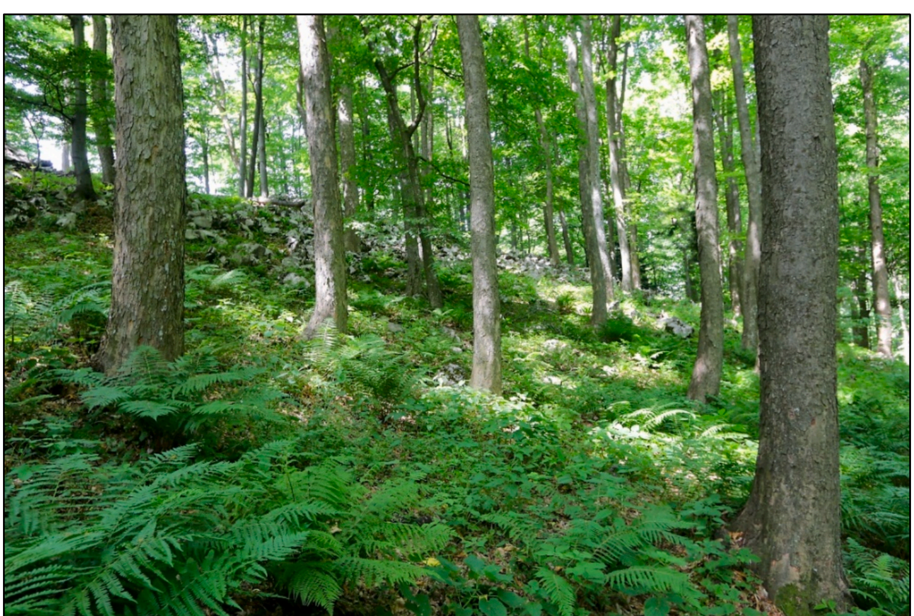

Fig. 2. A stand of ravine forest (*Tilio-Acerion*) in the Boč-Haloze-Donačka gora site with favourable conservation status. The composition of the tree species remains preserved, with evidence of regeneration of key tree species. No significant pressures or threats were observed. (Photo: L. Kutnar).

Fig. 3. A stand of ravine forest with a bad conservation status. Most *Fraxinus excelsior* trees are dying or in terminal decline due to invasive alien fungi. Trees in the regeneration layer are heavily browsed by wildlife. (Photo: L. Kutnar).

1. Altered tree species composition (e.g. conversion of noble broadleaf-dominated stands to those co-dominated by spruce);
2. Dieback of key tree species (caused by pests and pathogens, particularly invasive alien fungi);
3. Introduction of non-native, especially invasive, tree species;
4. Introduction and spread of other invasive non-native species (plants, animals, fungi, etc.);
5. Lack of regeneration of key tree species (due to inappropriate forest management, browsing or other biological factors);
6. Soil and tree damage from logging and harvesting operations;
7. Proximity to forest roads and skid trails (potentially causing damage to undergrowth, soil and springs due to wood transport);
8. Ground/Forest soil damage from off-road vehicle use (e.g. motorcycles, 4-wheelers, mountain bikes);
9. Litter raking (removal of dried leaves and small branches);
10. Changes in the hydrological regime (e.g. construction activities within the forest);
11. Various forms of soil and water pollution (including dumping of waste);
12. Negative effects of wildlife (browsing, trunk rubbing, trampling, digging, etc.);
13. Other pressures (e.g. open canopies caused by windstorms or snow, or recreational use of forest areas).

A comparison between the pressure classifications used in this study and the official categories used for Article 17 reporting (EEA, 2023b) is provided in Appendix 1.

Field assessments for all 81 study plots in the BHD site was carried out in the summer and autumn of 2021 and 2022, as part of the LIFE Integrated Project for Enhanced Management of Natura 2000 in Slovenia. Our fieldwork was conducted at sites that had been previously mapped and evaluated for conservation status (Kermavnar et al., 2023a). At each study plot, two datasets were collected to test for potential indicators of conservation status. The first set comprised 103 parameters associated with forest site and vegetation characteristics (see Table 1 and Appendix 2), based primarily on the European Assessment of Ground Vegetation protocol (Canullo et al., 2016). The second set comprised 58 parameters related to forest stand structure and composition and tree characteristics (Table 2 and Appendix 3), based on the Slovenian National Forest Inventory methodology (Skudnik et al., 2022; Pintar et al., 2024).

2.4. Data analysis

The data analysis was conducted in two stages. In the first stage, a preliminary screening assessed the relationship between the binary response variable and each plot-level explanatory variable derived from the vegetation assessment related to forest site and vegetation characteristics, and from the forest inventory associated with the structure of forest stands and tree characteristics (n = 161; Table 1 & 2 and Appendices 2 & 3). For each conservation status (binary response variable), we developed univariate models for logistic regression, i.e., a generalized linear model with binomial error distribution. For each model, the following statistics were extracted from the summary output: z-value, pseudo-R^2 and statistical significance. Significant results are reported in Appendix 4. Pseudo-R^2 was calculated as 1 – (residual deviance / null deviance) and was used as a measure of the explanatory power of predictive variables and for ranking significant predictors. All variables with a significant relationship ($p < 0.05$) were included in further analysis. In the second step, we employed Principal Component Analysis (PCA) based on the variables obtained in the first step. PCA, a multivariate technique, was used to identify variables that contributed most to explaining differences between conservation statuses. In addition, the potential multicollinearity problem was addressed by calculating the variance inflation factor and excluding highly correlated variables from the dataset through a stepwise procedure, using the vifstep function in the usdm package (Naimi, 2023). This correlation analysis was performed between the first step (univariate models) and the second step (PCA). The PCA function with automatic data standardization in the FactoMineR package (Husson et al., 2020) and visualizations were performed with the factoextra package (Kassambara and Mundt, 2020). All data analyses were conducted in R software version 4.3.0 (R Core Team, 2019).

3. Results

3.1. Pressures

In the studied ravine forests of the BHD site, the most common factors causing pressures on the stands of this habitat in the BHD site were identified as follows:

- Negative effects of wildlife (in 72.8 % of all plots);
- Dieback of key tree species (69.1 %);

Table 1
Merged description of parameters used for vegetation assessment, related to forest site and vegetation characteristics (For detailed parameter descriptions, see Appendix 2). Measurements and parameter estimates were in accordance with the European Assessment of Ground Vegetation; (Canullo et al., 2016).

Parameter	Description
Slope (SLOPE)	Angle between the ground surface under study and the apparent horizontal (in °)
Rockiness (ROCK)	Cover of outcropping rock and rock fragments (in % of plot surface)
Coarse woody debris (CWD)	Cover of coarse woody debris (in % of plot surface)
Cover of each vegetation layer	Cover of tree (T_COVER), shrub (S_COVER) and herb (H_COVER) layers (in % of plot surface) (Canullo et al., 2016)
Cover of mosses on different substrates	Cover of mosses on i) terricolous bryophytes on open soils (M_GROUND), ii) epilithic bryophytes on rocks and stones (M_ROCK), iii) epixylic bryophytes on deadwood and epiphytic bryophytes on the bark of living trees – from the base of the tree to a height of 2 m (M_WOOD) (in % of plot surface) (Kutnar et al., 2023a,b)
Cover of all mosses (M_COVER)	Cover of mosses on all different substrates (in % of plot surface) (Kutnar et al., 2023a,b)
Number of species in each vegetation layer	Number of different species in tree (T_NUMSP), shrub (S_NUMSP) and herb (H_NUMSP) layers; species nomenclature followed Tutin et al. (1993); Tutin et al. (1964–1980) and Martinčič et al. (2007)
Total number of species across all vegetation layers (ALL_NUMSP)	Total number of species in tree, shrub and herb layers (Tutin et al., 1993; Tutin et al., 1964-1980; Martinčič et al., 2007)
Shannon Diversity Index (H') in each vegetation layer	Shannon Diversity Index (H') in tree (T_SHANN), shrub (S_SHANN) and herb (H_SHANN) layers was calculated as follows: $H' = -\sum_{i=1}^{R} p_i \ln p_i$ – where p_i is a relative cover of species i in a record (Shannon, 1948)
Species Evenness Index (E) in each vegetation layer	Species Evenness Index (E) was calculated for tree (T_EVEN), shrub (S_EVEN) and herb (H_EVEN) layers as follows (Pielou, 1975):$E = \frac{H'}{\log(\text{species richness})}$
Cover of tree species in the tree (T) layer	Cover of all tree species in upper (T1) and lower (T2) tree layers was estimated by using the Barkman scale (Barkman et al., 1964; Canullo et al., 2016). The cover of following species was estimated: *Abies alba* (Abi alb_T1, Abi alb_T2), *Acer campestre* (Acecam_T2), *Acer platanoides* (Acepla_T1, Acepla_T2), *Acer pseudoplatanus* (Acepse_T1, Acepse_T2), *Alnus glutinosa* (Alnglu_T1), *Carpinus betulus* (Carbet_T1, Carbet_T2), *Castanea sativa* (Cassat_T1, Cassat_T2), *Fagus sylvatica* (Fagsyl_T1, Fagsyl_T2), *Fraxinus excelsior* (Fraexc_T1, Fraexc_T2), *Fraxinus ornus* (Fraorn_T1, Fraorn_T2), *Juglans regia* (Jugreg_T1, Jugreg_T2), *Ostrya carpinifolia* (Ostcar_T1, Ostcar_T2), *Picea abies* (Picabi_T1, Picabi_T2), *Prunus avium* (Pruavi_T1, Pruavi_T2), *Pseudotsuga menziesii* (Psemen_T2), *Quercus petraea* (Quepet_T1), *Robinia pseudoacacia* (Robpse_T2), *Salix caprea* (Salcap_T1), *Sorbus* aria (Sorari_T1, Sorari_T2), *Tilia cordata* (Tilcor_T1, Tilcor_T2), *Tilia platyphyllos* (Tilpla_T1, Tilpla_T2) and *Ulmus glabra* (Ulmgla_T1, Ulmgla_T2).
Cover of tree species in the shrub (S) layer	Cover of all tree species appearing in the shrub layer (S) was estimated using the Barkman scale (Barkman et al., 1964; Canullo et al., 2016). The cover of following species was estimated: *Abies alba* (Abi alb_S), *Acer campestre* (Acecam_S) *Acer platanoides* (Acepla_S), *Acer pseudoplatanus* (Acepse_S), *Carpinus betulus* (Carbet_S), *Castanea sativa* (Cassat_S), *Fagus sylvatica* (Fagsyl_S), *Fraxinus excelsior* (Fraexc_S), *Fraxinus ornus* (Fraorn_S), *Juglans regia* (Jugreg_S), *Ostrya carpinifolia* (Ostcar_S), *Picea abies* (Picabi_S), *Prunus avium* (Pruavi_S), *Pseudotsuga menziesii* (Psemen_S), *Pyrus pyraster* (Pyrpyr_S), *Quercus petraea* (Quepet_S), *Robinia pseudoacacia* (Robpse_S), *Sorbus* aria (Sorari_S), *Tilia cordata* (Tilcor_S), *Tilia platyphyllos* (Tilpla_S) and *Ulmus glabra* (Ulmgla_S).
Cover of tree species in the herb (H) layer	Cover of all tree species appearing in the herb layer (H) was estimated using the Barkman scale (Barkman et al., 1964; Canullo et al., 2016). The cover of following species was estimated: *Abies alba* (Abialb_H), *Acer campestre* (Acecam_H) *Acer platanoides* (Acepla_H), *Acer pseudoplatanus* (Acepse_H), Carpinus betulus (Carbet_H), *Castanea sativa* (Cassat_H), *Fagus sylvatica* (Fagsyl_H), *Fraxinus excelsior* (Fraexc_H), *Fraxinus ornus* (Fraorn_H), *Juglans regia* (Jugreg_H), *Ostrya carpinifolia* (Ostcar_H), *Picea abies* (Picabi_H), *Pinus strobus* (Pinstr_H), *Prunus avium* (Pruavi_H), *Pyrus pyraster* (Pyrpyr_H), *Quercus petraea* (Quepet_H), *Robinia pseudoacacia* (Robpse_H), *Sorbus* aria (Sorari_H), *Sorbus aucuparia* (Sorauc_H), *Sorbus torminalis* (Sortor_H), *Tilia cordata* (Tilcor_H), *Tilia platyphyllos* (Tilpla_H), *Ulmus glabra* (Ulmgla_H) and *Ulmus minor* (Ulmmin_H).

- Altered tree species composition (49.4 %);
- Proximity to forest roads and skid trails (34.6 %);
- Lack of regeneration of key tree species (28.4 %).

At the plot level, between 1 and 7 pressure factors were identified per plot. In plots in a favourable conservation status (Fig. 2), the most common pressures were (Table 3) i) negative effects of wildlife (recorded on 65.2 % out of 23 plots), ii) dieback of key tree species (43.5 %) and iii) lack of regeneration of key tree species (30.4 %). The most common pressures identified in plots in inadequate (unfavourable) conservation status were (Table 3) i) dieback of key tree species (76.1 % out of 46 plots), ii) negative effects of wildlife (71.7 %) and iii) altered tree species composition (60.9 %). The most common factors identified in plots in bad (poor) conservation status were (Fig. 3; Table 3) i) dieback of key tree species and ii) negative effects of wildlife (both 91.7 % out of 12 plots), and iii) altered tree species composition (58.3 %).

3.2. *Indicators of conservation status*

Univariate logistic regression models were employed as a preliminary test of the relationship between the binary response variable (conservation status; N = 3) and each plot-level explanatory variable (N = 161; see Tables 1 and 2, and Appendices 2–4). A set of 35 significant variables (out of 161) derived from the univariate logistic regression models was tested to exclude collinearity. Based on these models and the multicollinearity test, 21 variables were retained for PCA analysis.

The first PCA axis explained 22.6 % of the variation, and the second PCA axis explained 19.0 % (Figs. 4 and 5). The eigenvalues were 4.74 for PC1 and 4.00 for PC2. A clear separation of group centroids (defined by conservation status) was observed in the multivariate space (Figs. 4 and 5). Plots with stands in a favourable conservation status were mostly located at the top left of the PCA panel, while plots in bad conservation status were clustered at the bottom right. Most plots classified as inadequate (unfavourable) were located around the centre of the PCA, between the other two groups (Fig. 4).

All 21 significant predictive variables and their relative importance (contribution) to the first two dimensions (PC1 and PC2) are presented in Fig. 6 and Appendix 5. Variables with the highest relative importance (contribution) may be considered as indicators of the conservation status of the studied ravine forests. The main indicators of studied ravine forests were as follows: v1 – Rockiness (contribution of 9.11), i2 – Volume of *Tilia* species (8.45), v10 – Cover of *Tilia platyphyllos* in the shrub layer (7.24), v14 – Cover of *Acer pseudoplatanus* in the upper tree layer (7.19), v3 – Cover of the tree layer (7.09), i7 – Dead-to-living tree growing stock volume ratio (6.93), v12 – Number of species in the herb layer (5.69), v16 – Number of species in the shrub layer (5.56), v7 – Cover of *Fraxinus excelsior* in the upper tree layer (4.83), v18 – Cover of *Acer pseudoplatanus* in the herb layer (4.51), v17 – Cover of the herb layer (4.25), i5 – Number of trees with bark removal from the trunk (4.19), i16 – Volume of standing dead trees (3.90), i15 – Volume of lying dead trees (3.57), i11 – Stand density index (3.32), i10 – Mean diameter at breast height of the 5 largest trees (3.04), v4 – Species Evenness Index for the herb layer (3.02), v11 – Cover of *Tilia cordata* in the herb layer (2.43), v6 – Cover of all mosses (2.36), i13 – Number of dead or broken

Table 2
Merged description of forest inventory data associated with the structure of forest stands and tree characteristics (For detailed descriptions, see Appendix 3). Measurements and parameter calculations and estimates were adapted from the Slovenian National Forest Inventory (Skudnik et al., 2022; Pintar et al., 2024).

Parameters	Description
Number of trees (N/ha)	Total number of living trees (Tot_N), number of large living trees (DBH greater 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). DBH means diameter at breast height.
Basal area (m^2/ha) (BA)	Total basal area (BA) of living trees (Skudnik et al., 2021, Rybar et al., 2023).
Growing stock or volume (m^3/ha) (V)	Total growing stock (volume) of trees (Tot_V) (Pintar et al., 2024) and growing stock of prevailed tree species: *Acer pseudoplatanus* and *Acer platanoides* (Acer_V), *Tilia cordata* and *Tilia platyphyllos* (Tilia_V), *Fagus sylvatica* (Fagsyl_V), *Picea abies* (Picabi_V), *Acer pseudoplatanus* (Acepse_V), *Acer platanoides* (Acepla_V), *Fraxinus excelsior* (Fraexc_V), *Ulmus glabra* (Ulmgla_V), *Tilia cordata* (Tilcor_V), *Tilia platyphyllos*, (Tilpla_V), *Ostrya carpinifolia* (Ostcar_V).
Tree height	Mean (h_{mean}), maximum (h_{max}) and dominant (100 tallest trees per hectare) (h_{dom}) tree height (McElhinny et al., 2005, West, 2015, Tarmu et al., 2020, Pintar and Skudnik, 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 the 5 largest trees (DBH_5larg)	Mean diameter at breast height (cm) of the 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 $HDist_i$ is the Euclidean distance between the *i*-th tree and its nearest neighbour, *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: $GC = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}\left\|g_i - g_j\right\|}{2n^2\bar{g}}$ where g_i is basal area in size class *i* (Gini, 1921).
Shannon Diversity Index	Shannon Diversity Index of basal area heterogeneity for tree species (SH_BA_{spec}), 5 cm DBH classes (SH_BA_5) and 10 cm DBH classes (SH_BA_{10}): $H' = -\sum_{i=1}^{R} p_i \ln p_i$ – where p_i is the proportion of basal area of tree species or in 5 or 10 cm DBH classes (Shannon, 1948, Pintar and Hladnik, 2018, Pintar et al., 2024)
Evenness Index (E)	Evenness Index was calculated as follows: $E = \frac{SH}{\log_2 N}$, where *SH* is the Shannon Diversity Index (SH_BAspec) and *N* is the 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 the number of trees (N/ha) and d_g is the quadratic mean diameter (Reineke, 1933, Pintar and Hladnik, 2018).
Tree damage	For each tree, up to two types of tree damage were identified as having the greatest impact on its vitality (Skudnik et al., 2022). The following categories of tree damage were included in the analysis: total number of tree damage occurrences (T_dam), number of cracks (Cracks), number of damaged tree crowns (T_crown), number of broken tree trunks (T_trunks), number of dead or broken treetops (T_tops), number of cankers on trees (Cankers), number of cavities in trees (Cavities) and number of trees with bark removal from the trunk (Bark_rem).
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), volume of standing dead trees (StandD_V), volume of stumps (Stump_V), volume of snags (Snag_V), volume of coarse woody debris (CWD_V), deadwood volume in decay class 1 (recently dead) (Dec1_DWD_V), 2 (early decay) (Dec2_DWD_V), 3 (moderate decay) (Dec3_DWD_V) and 4 (advanced decay) (Dec4_DWD_V) (Skudnik et al., 2021, Borghi et al., 2024).
Naturalness (Natural)	Naturalness is divided into three categories (Skudnik et al., 2022): Forests without human management, sustainably managed forests and forests with altered tree composition.
Management (Managem)	Management is divided into four categories (Skudnik et al., 2022): unmanaged, management abandoned, managed (fresh stumps), managed (old stumps)
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).
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).
Regeneration (Regener)	The proportion of cover of tree species that are taller than 1.3 m and have a diameter at breast height of less than 10 cm (Skudnik et al., 2022).

treetops (1.91), i6 – Number of cavities in trees (1.40).

Indicators most strongly associated with favourable conservation status of studied ravine forests were as follows: Rockiness (v1), Volume of both *Tilia* species (i2), Cover of *Tilia platyphyllos* in the shrub layer (v10), Cover of the tree layer (v3) and Cover of *Acer pseudoplatanus* in the upper tree layer (v14). Vectors of these variables are the longest and point clearly to stands in a favourable conservation status in Fig. 5.

Conversely, indicators associated with bad conservation status were as follows: Dead-to-living tree growing stock volume ratio (i7), Number of species in the shrub layer (v16) and in the herb layer (v12), Cover of *Fraxinus excelsior* in the upper tree layer (v7), Cover of the herb layer (v17), Cover of *Acer pseudoplatanus* in the herb layer (v18), Volume of standing dead trees (i16), and Volume of lying dead trees (i15) (Fig. 5).

4. Discussion

The proper management of Natura 2000 habitats and sites requires improved knowledge of their spatial distribution, ecological characteristics and reliable indicators. This study focused on indicators related to stand structure and functions, as well as typical species of ravine forests belonging to the European priority forest habitat type of *Tilio-Acerion* forests of slopes, screes and ravines (9180*). Although these stands cover rather small areas in the Natura 2000 BHD site, we observed significant variation in their structure, composition and conservation status.

4.1. Conservation status, pressures and threats

Most stands in the surveyed plots (85 %) were found to be in favourable or at least inadequate (unfavourable) conservation status, which is comparable to or better than the conservation status of habitat type 9180* in other European countries (ETC/BD & EEA, 2018; EEA, 2025). Their occurrence in specific site conditions and smaller areas is typical for ravine forests and potentially increases the risk of further fragmentation. *Tilia*-dominated stands with thermophilous broadleaves, which occur on extreme rocky sites on ridges and slopes in the studied BDH site, may be particularly vulnerable to future habitat fragmentation. Fragmentation has already been identified as one of the major threats to ravine forests in Slovenia and beyond (Dakskobler et al., 2013; Kutnar and Dakskobler, 2014; EC, 2013).

Table 3
Pressures (IDs 1–13, see list below) by conservation status at the plot level, shown as the percentage of plots in each conservation status group. *Legend: 1. Altered tree species composition; 2. Dieback of key tree species; 3. Introduction of non-native, especially invasive tree species; 4. Introduction and spread of other invasive non-native species; 5. Lack of regeneration of key tree species; 6. Soil and tree damage from logging and harvesting; 7. Proximity to forest roads and skid trails; 8. Ground/Forest soil damage from off-road vehicle use in forest areas; 9. Litter raking; 10. Changes in the hydrological regime; 11. Various forms of soil and water pollution, including waste; 12. Negative effects of wildlife; 13. Other pressures.*

Factor ID	Favourable c.s. (in %; N = 23)	Inadequate c.s. (in %; N = 46)	Bad c.s. (in %; N = 12)
1	21.7	60.9	58.3
2	43.5	76.1	91.7
3	4.3	6.5	8.3
4	4.3	13.0	16.7
5	30.4	30.4	16.7
6	8.7	8.7	0.0
7	21.7	41.3	33.3
8	0.0	2.2	0.0
9	0.0	0.0	0.0
10	0.0	4.3	0.0
11	4.3	28.3	33.3
12	65.2	71.7	91.7
13	0.0	10.9	0.0
Average No. of factors per plot	2.0	3.5	3.5

Observations at the plot level partially confirmed the findings from a previous preliminary study on ravine forests (Kermavnar et al., 2023a). A detailed analysis of pressures showed that nearly three quarters of the plots were negatively affected by wildlife. Browsing, which prevents the establishment of key tree species in the shrub and tree layers, was identified as both a significant current pressure and a threat to the future development and conservation of ravine forests. In addition to native deer species, significant browsing impact was caused by the population of mouflon (*Ovis musimon* Pallas), a non-native species introduced to the Boč area decades ago and still maintained for hunting purposes. Browsing of juvenile trees by various wildlife species negatively affects the ecological conditions for native species and hinders the natural development of ravine forests throughout the BHD site (Karlo and Senegačnik, 2020). Observations and measurements by the Slovenia Forest Service on a systematic plot grid in the study area revealed that key tree species of ravine forests, such as *Acer pseudoplatanus* and *Fraxinus excelsior*, were rare in the regeneration layer at heights over 60 cm, primarily due to browsing pressure, particularly by mouflon (SFS, 2019, 2022a,b). The lack of natural regeneration is a major long-term threat, as it determines the species composition of future mature stands. A lack of *Acer pseudoplatanus* ingrowth has already been documented in other Slovenian forests (Kušar and Kovač, 2023). Solving wildlife management issues will require coordinated efforts from all stakeholders (foresters, hunters, forest owners and conservationists) (Reimoser, 2003).

Another major threat to the long-term existence of ravine forests in favourable condition is the decline in vitality or even complete dieback of key tree species, mostly caused by invasive alien fungi (Jurc et al., 2006; Ogris et al., 2009). This appears to be the main reason for the poorer condition of the forests in plots with bad or inadequate (unfavourable) conservation status. A higher proportion of plots with bad

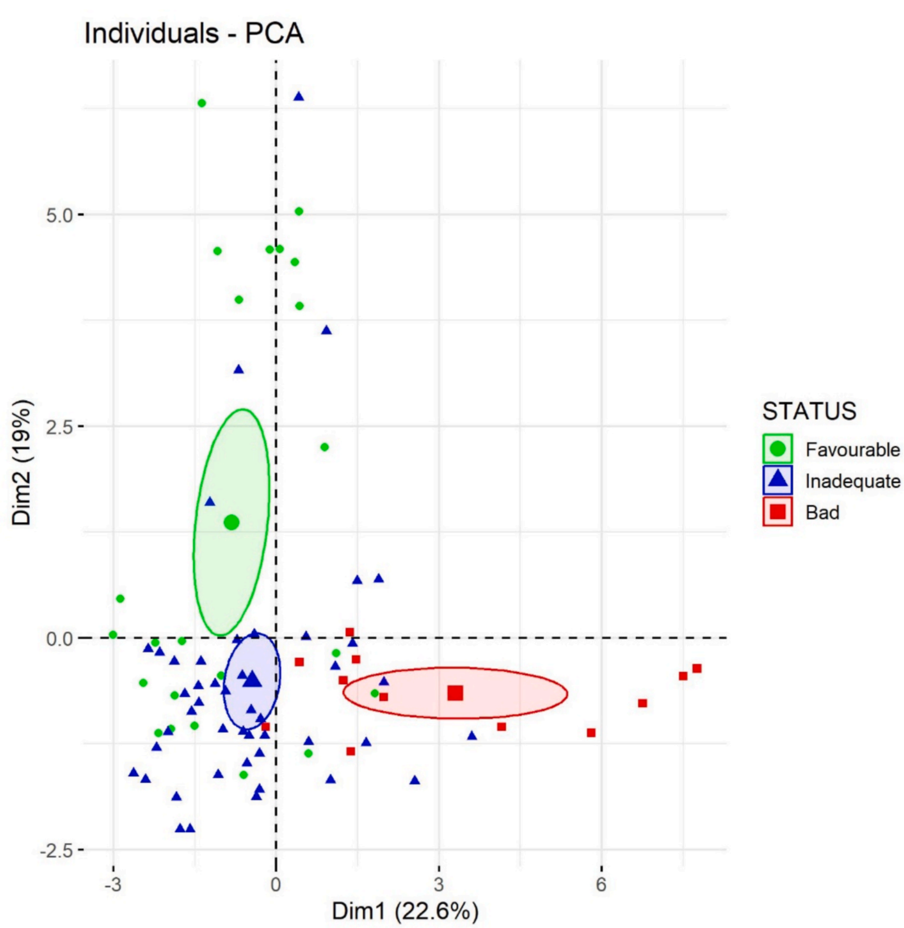

Fig. 4. Results of principial component analysis based on 21 significant predictive variables. The figure shows the distribution of plots and groups (conservation status) in the ordination space. Large symbols represent group centroids, which are surrounded by confidence ellipses.

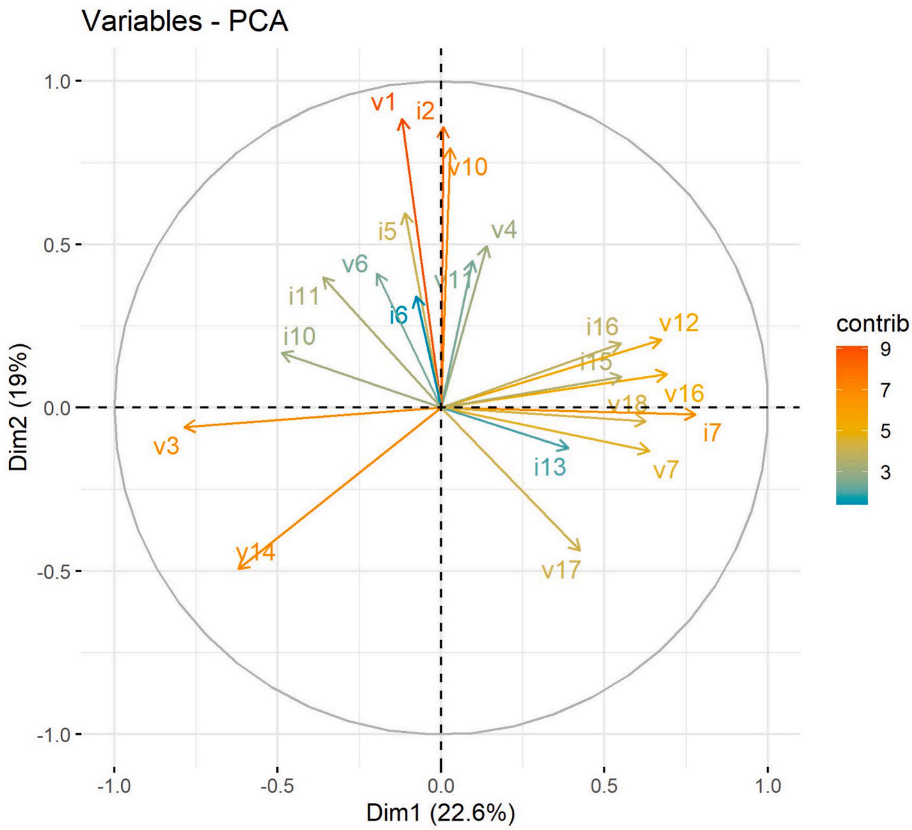

Fig. 5. PCA biplot based on 21 significant predictive variables. Variables explaining the PCA multivariate space are colour-coded according to their contribution. Variables are labelled as follows: v1 = ROCK, i2 = Tilia_V, v10 = Tilpla_S, v14 = Acepse_T1, v3 = T_COVER, i7 = DLR, v12 = H_NUMSP, v16 = S_NUMSP, v7 = Fraexc_T1, v18 = Acepse_H, v17 = H_COVER, i5 = Bark_rem, i16 = StandD_V, i15 = LyingD_V, i11 = SDI, i10 = DBH_5larg, v4 = H_EVEN, v11 = Tilcor_H, v6 = M_COVER, i13 = T_tops, i6 = Cavities. Variable descriptions are provided in Tables 1 and 2 and Appendices 2 and 3.

status were dominated by European ash (*Fraxinus excelsior*), which has suffered high mortality due to the invasive alien fungal disease known as ash dieback (*Chalara fraxinea*) (Ogris et al., 2009; Pautasso et al., 2013). This pathogen is a widespread conservation problem across Europe, as it is lethal to ash trees of all ages and causes high tree mortality. In addition to ash, other tree species such as *Ulmus glabra* and *Acer pseudoplatanus* are also threatened by pest infestations. This is reflected in the high volume of lying and standing dead trees in the analysed area (24.8 m^3/ha), which is significantly higher than the mean deadwood volume in Slovenian forests (14.8 m^3/ha) (Skudnik et al., 2021; Kušar and Neumann, 2024).

A third common factor contributing to bad (poor) conservation status was altered tree species composition. This was particularly evident in plots with bad or inadequate conservation status. One reason is the small size of ravine forests within a broader matrix of European beech forests (Babij et al., 2020). Beech competition in the ravine forest stands, already identified in the preliminary study (Kermavnar et al., 2023a), was also confirmed to be an important factor at the plot level. With 32 % of the growing stock in Slovenian forests, beech is the dominant tree species (Skudnik et al., 2021; Pintar et al., 2024), and its high shade tolerance makes it more competitive in the regeneration layer, often outcompeting noble broadleaves such as *Acer* spp. and *Fraxinus excelsior*. In addition, the current altered tree species composition is also a consequence of past forest management favouring the planting of Norway spruce (*Picea abies*), which ranks second in growing stock in Slovenia (28 %), although its share has been declining since 2000 (Skudnik et al., 2021; Pintar et al. 2024) due to the impact of climate change and disturbances (Kutnar et al., 2021; Kermavnar et al., 2023b). Since Beech and spruce are also the most common tree species in Central Europe (Leuschner and Ellenberg, 2017), their influence on the composition of ravine forests likely extends beyond Slovenia. These human-induced changes in tree species composition have reduced forest naturalness and negatively impacted the conservation status of ravine forests throughout Slovenia (Kutnar et al., 2011).

Climate change is another factor expected to shape the future development of ravine forests. It is likely to interact with abiotic and anthropogenic disturbances and have a significant impact on temperate beech forests in Slovenia (Kutnar and Kobler, 2011; Kutnar et al., 2011; Kutnar et al., 2021; Gregorčič et al., 2023). The beech-dominated forest zone in Slovenia also encompasses fragmented ravine forests. Furthermore, modelled projections for *Tilio-Acerion* forests in Bavaria suggested a significant reduction to around two-thirds of their current size by the 2070 s under the RCP8.5 climate scenario (Steinacker et al., 2019).

Climate change is also likely to influence the spread of pathogens that cause dieback of key tree species in ravine forests, thus affecting their conservation status and future development. Drought stress caused by climate warming is expected to increase the pathogenicity of some disease agents of key tree species (Ogris et al., 2021). In addition to the well-known ash dieback caused by the *Chalara fraxinea* fungus (Ogris et al., 2009) and other ash diseases (Linaldeddu et al., 2022), which have frequently been observed in the study plots, the future status and development of ravine forests may also be significantly affected by pathogens of *Acer pseudolatanus*, such as *Eutypella parasitica* canker (Jurc et al., 2006; Brglez et al., 2020), as well as others (Brglez et al., 2020; Ogris et al., 2021; Brglez et al., 2024). Large areas of Europe's natural maple distribution are at significant risk of infection by *Eutypella parasitica*, with the most endangered regions likely to be large parts of the Balkans (including Slovenia), the Apennines, France, Central and Eastern Europe, and the Caucasus (Ogris et al., 2006).

As already discussed in Kermavnar et al. (2023), the bad (poor) and

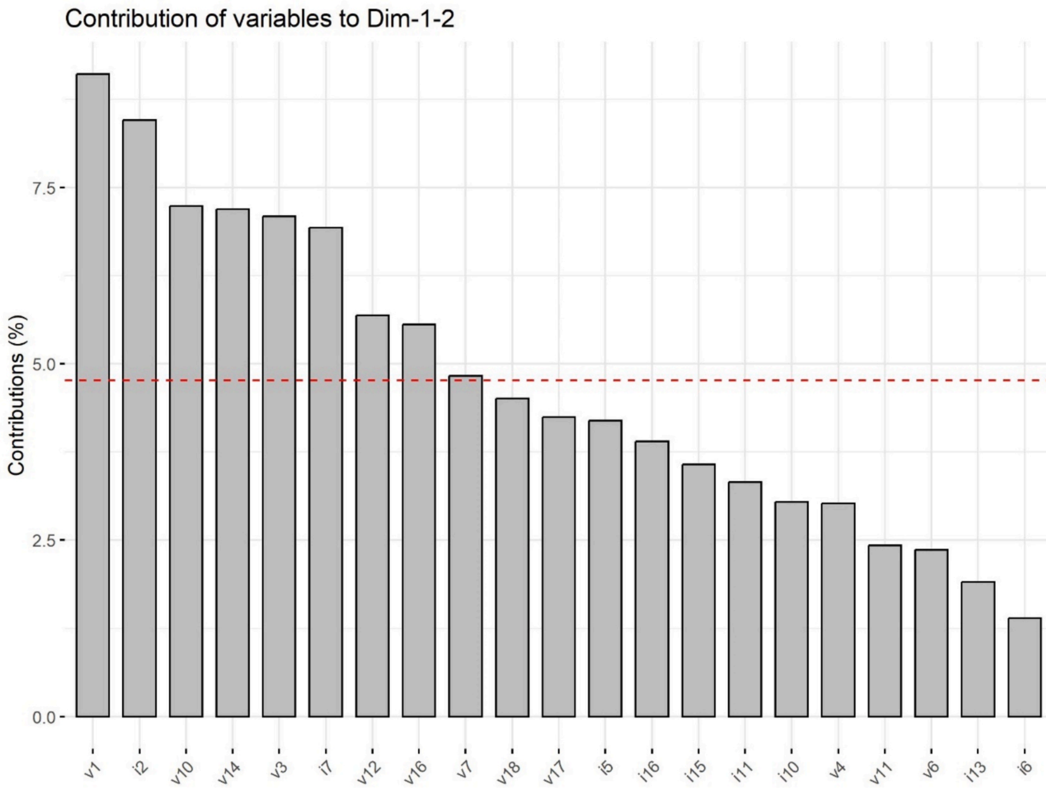

Fig. 6. Ranking of all variables according to their contribution (relative importance) to the first two PCA dimensions (PC1 and PC2). Variables are labelled as follows: v1 = ROCK, i2 = Tilia_V, v10 = Tilpla_S, v14 = Acepse_T1, v3 = T_COVER, i7 = DLR, v12 = H_NUMSP, v16 = S_NUMSP, v7 = Fraexc_T1, v18 = Acepse_H, v17 = H_COVER, i5 = Bark_rem, i16 = StandD_V, i15 = LyingD_V, i11 = SDI, i10 = DBH_5larg, v4 = H_EVEN, v11 = Tilcor_H, v6 = M_COVER, i13 = T_tops, i6 = Cavities. Variable descriptions are provided in Tables 1 and 2 and Appendices 2 and 3.

inadequate conservation status of ravine forests is the result of a complexity of many different negative factors and their interactions. Up to seven negative pressure factors per plot were identified in the present study. In addition to mortality of key tree species caused by invasive alien fungi, altered tree species composition and hindered natural regeneration by wildlife, the lack of young succession phases studied in Kutnar et al. (2011) also poses a serious threat to the studied ravine forests, ultimately compromising the integrity of the existing habitat type to such an extent that the development of a new trajectory is unavoidable. If regeneration patterns do not change and pressure from herbivorous species and pathogens on key tree species remains high, mesophile forest stands currently composed of species typical of ravine forests could gradually be replaced by beech, a more shade-tolerant and competitive species, except in some more extreme warm *Tilia*-dominated sites with thermophilous broadleaves. However, according to long-term climate change predictions (Kutnar et al., 2011, 2021; Gregorčič et al., 2023), it is possible that most of the key species in the ravine forests would be replaced by broadleaves that prefer warmer climates. The ravine forests under study are likely to undergo drastic changes in response to natural disturbances (e.g. pest outbreaks, wildlife browsing and windthrow), competition from beech and thermophilous broadleaves, climate warming and other human-induced impacts. These changes could significantly alter the composition of tree species and stand structure, potentially disrupting the stability of the forests and even endangering their future existence in the study area. Therefore, to ensure a favourable conservation status and existence of these forests in future, appropriate management and restoration actions should be regularly implemented in ravine forests (Simonson et al., 2013).

The forest management of the studied ravine forests is based on the forest management plans of three units (SFS, 2019; 2022a,b). These forests are generally managed according to close-to-nature, sustainable and multifunctional principles that include selective cutting and small-scale shelterwood logging. However, some active and targeted forest management measures should be implemented to reduce the harmful effects of disturbances and climate change. In addition to reducing wildlife populations, particularly the non-native mouflon, which have negative effects on ravine forests, concrete forest management measures are needed to ensure the long-term survival of these forests. During the regeneration phase, noble deciduous tree species such as *Acer pseudoplatanus*, *Fraxinus excelsior* and *Tilia* species should be promoted or even planted additionally. Since these species require light, sufficiently large gaps should be formed to ensure that enough sunlight reaches the forest floor, thereby increasing the competitiveness of these tree species during the regeneration phase.

In areas with high wildlife pressure, patches of the forest in the regeneration phase that are dominated by noble deciduous trees can be fenced to prevent browsing. The final form of ravine forest would be clumped or grouped stands with an uneven structure, which would enhance the resilience and resistance of the forest to increasingly frequent natural disturbances. Pest and disease outbreaks in ravine forest will probably remain the most challenging issue in future. Active forest management involving the regular sanitary felling of degraded stands with a high number of infested trees should be implemented. Discovering the presence of defence mechanisms that limit fungal growth or promote disease resistance of trees will be important, presuming that some individual trees are resistant to dieback caused by invasive pathogens (Hauptman et al., 2016).

Some of the most well-preserved stands of ravine forest should be protected within existing or additional forest reserves in the study area. Otherwise, they could be protected within eco-cells, a valuable tool for maintaining the favourable conservation status of certain stands of ravine forests. An eco-cell is a specific conservation measure that covers a small part of the forest and is left to develop naturally as much as possible in order to preserve specific habitats or species.

4.2. Indicators of conservation status

The total area and average size of ravine forest stands in the BHD area were found to be small (Kermavnar et al., 2023a). However, considerable variation was observed in their site and stand characteristics. Some of these forests, such as those dominated by *Tilia* species on very rocky and steep slopes in remote areas, are less intensively managed and play a significant protective role. Contrary to the findings of a previous study (Baran et al., 2020), which reported a lack of tree clusters in managed ravine forests, field data from the present study recorded a high frequency of tree clusters with multiple stems (data not shown), particularly *Tilia*-dominated stands. This may confirm the lower management intensity of these stands. The favourable conservation status of these ravine forests was indicated by several factors related to the presence and characteristics of *Tilia* species, such as their growing stock (volume) and cover. The absence of or only limited management in these *Tilia*-dominated forests, which are located in more extreme and less accessible areas, is further supported by a higher proportion of outcropping rocks and rock fragments on the forest floor. These site characteristics also contribute to their favourable conservation status. Furthermore, due to their specific site and stand conditions, *Tilia*-dominated forests have been identified as one of the four specific subtypes of the *Tilio-Acerion* habitat type in Slovenia (Kermavnar et al., 2023a).

Based on the findings of previous studies (e.g. Cantarello and Newton, 2008; Kutnar et al., 2011), tree species composition was also found to be a cost-effective and easily obtained indicator of forest ecosystems and their conservation status (Kutnar and Dakskobler, 2014; Kovač et al., 2020), with high predictive power. Cover of *Tilia* species and *Fraxinus excelsior* in the tree layer had a high indicative value for conservation status, as both grow under more specific site conditions in the studied ravine forests and are also characteristic species for certain subtypes of the *Tilio-Acerion* habitat type in Slovenia. In contrast, *Acer pseudoplatanus* occurred throughout the entire range of the studied ravine forest stands and was not strictly limited to specific subtypes (Kermavnar et al., 2023a).

Clusters with multiple stems of *Tilia* species can also significantly contribute to a higher volume of growing stock, which was also shown to be an indicator of a favourable conservation status in the studied ravine forests. Growing stock is a frequently used indicator in forest biodiversity studies (Chirici et al., 2011; Kovač et al., 2016). Although the quantity of wood itself may not directly reflect the conservation status of the forest habitat type, this indicator helps to reveal important components of the forest habitat type (Kovač et al., 2020).

Since the early days of forest inventories, tree diameter has been one of the most commonly used forestry variables, particularly for calculating tree and stand basal areas (Husch et al., 2002) and other similar indices (Kovač et al., 2020). In addition to being an indicator of favourable conservation status of the habitat type itself, large trees are important as microhabitats and for supporting populations of typical and key habitat species (Kraus et al., 2016; Tinya et al., 2021). Large trees also contribute to the conservation of plant and animal species that are sensitive to logging and require longer forest age thresholds, especially in managed stands (Gustafsson et al., 2004; Moning and Müller, 2009).

Our study has shown that in *Tilio-Acerion* forests, more complex structural indicators (e.g. the Gini coefficient or the Clark and Evans index) do not reflect conservation status better than simpler parameters (e.g. total stand and deadwood volume). This is likely due to the lower diversity of tree diameters in these forests, which results from the dominance of light-demanding tree species. However, these indicators are expected to exhibit greater explanatory power in forests where shade-tolerant species are present, such as Illyrian beech forests, which are among the most heterogeneous in Slovenia (Trifković et al., 2023).

Contrary to the common understanding that deadwood plays a beneficial role in forest ecosystems (Lassauce et al., 2011) by contributing to future mineral cycling (Kovač et al., 2020), providing a substrate for tree seedling germination and recruitment, and offering habitat for many animal and plant species (Harmon et al., 1986; Christensen et al., 2005; Paletto et al., 2012), in this study deadwood was more indicative of bad (poor) conservation status in the studied ravine forests. Several deadwood-related indicators, such as the ratio of dead to live tree volume, volume of standing dead trees and volume of lying dead trees, mostly reflected dieback of key tree species, especially *Fraxinus excelsior*. Although deadwood may provide future ecological benefits, its current high levels result from the degradation of *Fraxinus excelsior*-dominated stands caused by widespread fungal disease (Ogris et al., 2009; Pautasso et al., 2013). Additional mortality of other key species in ravine forests, particularly maples, has been linked to various pest infestations (Jurc et al., 2006; Brglez et al., 2020; Ogris et al., 2021; Brglez et al., 2024).

Increased mortality of key and dominant tree species in ravine forests has resulted in higher light intensity at the forest floor. In degraded stands with bad conservation status, this change was reflected in a higher number of plant species in the herb and shrub layer, and greater cover of the herb layer. A comparable post-disturbance response in the forest herb layer, characterized by an increase in resident species coupled with colonisation of early successional, non-forest species, was also observed in Illyrian beech forest stands (Kutnar et al., 2015; Kermavnar et al., 2019), which is the dominant habitat type in the Natura 2000 network in Slovenia. The light transmittance of the tree layer is considered one of the most important drivers shaping the understory environment and influencing herb layer species richness in temperate deciduous forests (Dormann et al., 2020). Changes in light conditions in these stands were also indicated by increased cover of young *Acer pseudoplatanus* trees in the herb layer. As a light-demanding species, *Acer pseudoplatanus* seedlings grow rapidly in full light and on suitable sites, outcompeting other more shade-tolerant tree species such as beech (Hein et al., 2008).

5. Conclusions

This study provided a preliminary test of conservation status indicators for the EU priority habitat *Tilio-Acerion* forests. We have shown that structural and compositional variables derived from forest site and vegetation assessments, as well as forest inventories focused on forest stand structure and tree characteristics, can be serve as valuable explanatory and discriminating variables that effectively indicate the conservation status of these ravine forests. In addition to the documented pressures and threats, specific conservation status indicators can assist nature conservationists and forest managers in decision-making, supporting the implementation of appropriate conservation measures to maintain or even improve the status of these ravine forests. As demonstrated in this study, identifying conservation status indicators based on structural and compositional characteristics holds significant potential for the monitoring and management of other Natura 2000 habitat types and other ecologically important forests. The results also provide a useful methodological framework for the long-term monitoring of this habitat type, which will support reporting under Article 17 of the Habitats Directive (1992). In conclusion, effective conservation strategies for maintaining and improving the conservation status of Natura 2000 forest habitats must consider conservation status indicators that are closely linked to the ecological specificity of habitats and to the associated pressures and threats.

CRediT authorship contribution statement

Lado Kutnar: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology,

Investigation, Funding acquisition, Data curation, Conceptualization. **Janez Kermavnar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anže Martin Pintar:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, 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.2025.114079.

Data availability

Data will be made available on request.

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