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Improvement of the conservation status of forest habitats in the Mediterranean Biogeographical Region applying restoration and conservation techniques and close to nature management

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Milestone 1

Indicators validation report

WP2 - Assessment of the conservation status of habitats 9340, 9330, 9260 and 9530*

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Index

Summary

Mediterranean forests are under significant threat from both extreme natural events and changes in human activities. Defining standardised systems for recognizing, classifying, and assessing the conservation status of these habitats is crucial, but appropriate criteria and indicators, as well as tailored management strategies are still lacking. For these reasons, the GoProForMed project aims to improve or maintain the conservation status of four specific forest habitats dominated by *Quercus suber*, *Quercus ilex* or *Quercus rotundifolia*, *Castanea sativa*, and endemic blackpines in Italy, Spain, France, and Greece. By defining common strategies for habitat classification, conservation status assessment, and close-to-nature forest management, the project seeks to contribute to the conservation of these habitats and their biodiversity.

This report focuses on adapting and testing methods for forest biodiversity monitoring, particularly structure-based indicators like Tree-related Microhabitats (TreMs), the Index of Biodiversity Potential (IBP), and other structural attributes such as tree diameter distributions and deadwood decay classes. Biodiversity surveys were conducted across 72 sampling units in 12 sites, covering vascular plants, epiphytic lichens, arthropods, birds, bats, and forest structure.

Response variables were chosen for each taxonomic group: relative cover of diagnostic species for vascular plants, Shannon index for epiphytic lichens, number of functional groups for arthropods, and richness and Shannon index for birds and bats.

The modelling framework was based on Boosted Regression Trees (BRTs), except for those based targeting birds and bats, for which a qualitative analysis was conducted due to the limited number of sampling units.

Key findings indicate that canopy cover and TreM abundance significantly influence plant and epiphytic lichen diversity, though with opposing effects for canopy cover. Saproxylic beetles' diversity was linked to deadwood quality, TreMs, and IBP, while phytophagous arthropods preferred lower tree density and higher shrub cover. The diversity of bird and bat communities showed weak connections to IBP values. The study highlights the importance of the IBP for monitoring biodiversity, with correlations to saproxylic and phytophagous insects and lichens. However, the IBP should give more weight to canopy openness in Mediterranean forests.

The optimal range for canopy cover is suggested to be 50-70% for effective biodiversity conservation, allowing for the development of the shrub layer. The abundance of TreM-bearing senescent trees and advanced decay-stage deadwood is vital for supporting biodiversity, especially when combined with long-term ecological continuity.

Despite the limitations imposed by a relatively small sample size, this work provides essential insights for Mediterranean forest management and conservation, emphasizing the need for further data to refine recommendations, particularly for bats and birds.

Résumé

Les forêts méditerranéennes sont gravement menacées par des événements naturels extrêmes et des changements dans les activités humaines. La définition de systèmes standardisés pour reconnaître et évaluer l'état de conservation de ces habitats est cruciale, mais les critères et indicateurs appropriés, ainsi que des stratégies de gestion adaptées, font encore défaut. Pour ces raisons, le projet GoProForMed vise à améliorer ou maintenir l'état de conservation de quatre habitats forestiers dominés par *Quercus suber*, *Quercus ilex* ou *Quercus rotundifolia*, *Castanea sativa*, et des pins noirs endémiques en Italie, Espagne, France et Grèce. En définissant des stratégies communes pour la classification, l'évaluation de l'état de conservation et la gestion, le projet cherche contribue à la conservation de ces habitats et de leur biodiversité.

Ce rapport se concentre sur l'adaptation et le test de méthodes pour le suivi de la biodiversité forestière, en particulier des indicateurs basés sur la structure tels que les microhabitats liés aux arbres (TreMs), l'Indice de Biodiversité Potentiel (IBP) et d'autres attributs structuraux. Des enquêtes sur la biodiversité ont été menées dans 72 unités d'échantillonnage réparties sur 12 sites, couvrant les plantes vasculaires, les lichens épiphytes, les arthropodes, les oiseaux, les chauves-souris et la structure des forêts.

Des variables de réponse ont été choisies pour chaque groupe taxonomique: le couvert relatif des espèces diagnostiques pour les plantes vasculaires, l'indice de Shannon pour les lichens épiphytes, le nombre de groupes fonctionnels pour les arthropodes, et la richesse ainsi que l'indice de Shannon pour les oiseaux et les chauves-souris.

La modélisation reposait sur des Boosted Regression Trees, sauf pour les oiseaux et les chauves-souris, pour lesquels une analyse qualitative a été réalisée.

Les résultats montrent que le couvert forestier et l'abondance de TreMs influencent significativement la diversité des plantes et des lichens épiphytes, bien que de manière opposée pour le couvert forestier. La diversité des coléoptères saproxyliques est liée à la qualité du bois mort, aux TreMs et à l'IBP, tandis que les arthropodes phytophages préfèrent un couvert arbustif plus élevé. La diversité des communautés d'oiseaux et de chauves-souris présente des liens faibles avec les valeurs de l'IBP.

Cette étude indique l'IBP comme efficace pour le suivi de la biodiversité, avec des corrélations pour les insectes saproxyliques et phytophages et les lichens. Cependant, l'IBP devrait accorder une plus grande importance à l'ouverture du couvert forestier dans les forêts méditerranéennes, valeurs de 50-70% peut favoriser la conservation de la biodiversité, tout en permettant le développement de la strate arbustive.

L'abondance d'arbres sénescents et la présence de bois mort à un stade avancé de décomposition sont essentielles pour soutenir la biodiversité, particulièrement lorsqu'elles sont combinées avec une longue continuité écologique. Malgré des limites, ce travail offre des perspectives essentielles pour la gestion et la conservation des forêts méditerranéennes.

Resumen

Las bosques mediterráneas están seriamente amenazadas por eventos naturales extremos y cambios en las actividades humanas. Definir sistemas estandarizados para reconocer y evaluar el estado de conservación de estos hábitats es crucial, pero aún faltan los criterios e indicadores apropiados, así como estrategias de gestión adaptadas. Por estas razones, el proyecto GoProForMed tiene como objetivo mejorar o mantener el estado de conservación de cuatro hábitats forestales dominados por Quercus suber, Quercus ilex o Quercus rotundifolia, Castanea sativa y pinos negros endémicos en Italia, España, Francia y Grecia. Al definir estrategias comunes para la clasificación, la evaluación del estado de conservación y la gestión, el proyecto busca contribuir a la conservación de estos hábitats y su biodiversidad.

Este informe se centra en la adaptación y prueba de métodos para el monitoreo de la biodiversidad forestal, particularmente indicadores basados en la estructura, como los microhábitats relacionados con los árboles (TreMs), el Índice de Biodiversidad Potencial (IBP) y otros atributos estructurales. Se realizaron encuestas de biodiversidad en 72 unidades de muestreo repartidas en 12 sitios, cubriendo plantas vasculares, líquenes epifíticos, artrópodos, aves, murciélagos y la estructura del bosque.

Se eligieron variables de respuesta para cada grupo taxonómico: la cobertura relativa de especies diagnósticas para las plantas vasculares, el índice de Shannon para los líquenes epifíticos, el número de grupos funcionales para los artrópodos y la riqueza, así como el índice de Shannon para aves y murciélagos. La modelización se basó en árboles de regresión aumentada, excepto para las aves y murciélagos, para los que se realizó un análisis cualitativo.

Los resultados muestran que la cobertura forestal y la abundancia de TreMs influyen significativamente en la diversidad de plantas y líquenes epifíticos, aunque de manera opuesta para la cobertura forestal. La diversidad de los escarabajos saproxílicos está relacionada con la calidad de la madera muerta, los TreMs y el IBP, mientras que los artrópodos fitófagos prefieren una mayor cobertura arbustiva. La diversidad de las comunidades de aves y murciélagos presenta vínculos débiles con los valores del IBP.

Este estudio indica que el IBP es eficaz para el seguimiento de la biodiversidad, con correlaciones para insectos saproxílicos y fitófagos, y líquenes. Sin embargo, el IBP debería dar más importancia a la apertura del dosel forestal en los bosques mediterráneos. Valores de 50-70% de cobertura forestal favorecen la conservación de la biodiversidad, permitiendo también el desarrollo de la capa arbustiva.

La abundancia de árboles senescentes y la presencia de madera muerta en etapas avanzadas de descomposición son esenciales para apoyar la biodiversidad, especialmente cuando se combinan con una larga continuidad ecológica. A pesar de las limitaciones, este trabajo ofrece perspectivas esenciales para la gestión y conservación de los bosques mediterráneos.

Sommario

I boschi mediterranei sono gravemente minacciati da eventi naturali estremi e cambiamenti nelle attività umane. La definizione di sistemi standardizzati per riconoscere e valutare lo stato di conservazione di questi habitat è cruciale, ma mancano ancora criteri e indicatori appropriati, nonché strategie di gestione adattate. Per queste ragioni, il progetto GoProForMed mira a migliorare o mantenere lo stato di conservazione di quattro habitat forestali dominati da *Quercus suber*, *Q. ilex* o *Q. rotundifolia*, *Castanea sativa* e pini neri (*Pinus nigra*) endemici in Italia, Spagna, Francia e Grecia. Definendo strategie comuni per la classificazione, la valutazione dello stato di conservazione e la gestione forestale, il progetto cerca di contribuire alla conservazione di questi habitat e della loro biodiversità.

Questo rapporto si concentra sull'adattamento e il test di metodi per il monitoraggio della biodiversità forestale, in particolare indicatori basati sulla struttura, come i microhabitat legati agli alberi (TreMs), l'Indice di Potenziale di Biodiversità (IBP) e altri attributi strutturali. Le indagini sulla biodiversità sono state condotte in 72 unità di campionamento distribuite su 12 siti, coprendo piante vascolari, licheni epifiti, artropodi, uccelli, pipistrelli e la struttura del bosco.

Sono state selezionate variabili di risposta per ciascun gruppo tassonomico: la copertura relativa delle specie diagnostiche per le piante vascolari, l'indice di Shannon per i licheni epifiti, il numero di gruppi funzionali per gli artrópodi, e la ricchezza e l'indice di Shannon per uccelli e pipistrelli. La modellizzazione si è basata su alberi di regressione potenziata, salvo per gli uccelli e i pipistrelli, per i quali è stata effettuata un'analisi qualitativa.

I risultati mostrano che la copertura del bosco e l'abbondanza di TreMs influenzano significativamente la diversità di piante e licheni epifiti, sebbene con effetti opposti per la copertura del bosco. La diversità degli scarabei saproxilici è legata alla qualità del legno morto, ai TreMs e all'IBP, mentre gli artrópodi fitofagi preferiscono una maggiore copertura arbustiva. La diversità delle comunità di uccelli e pipistrelli mostra legami deboli con i valori dell'IBP.

Questo studio suggerisce che l'IBP è efficace per il monitoraggio della biodiversità, con correlazioni per gli insetti saproxilici, fitofagi e licheni. Tuttavia, l'IBP dovrebbe attribuire maggiore importanza all'apertura del coperto forestale nei boschi mediterranei. Valori di copertura forestale tra il 50 e il 70% possono favorire la conservazione della biodiversità, permettendo al contempo lo sviluppo della vegetazione arbustiva.

L'abbondanza di alberi senescenti e la presenza di legno morto in avanzate fasi di decomposizione sono essenziali per sostenere la biodiversità, soprattutto quando sono combinate con una lunga continuità ecologica. Nonostante le limitazioni, questo lavoro offre prospettive essenziali per la gestione e la conservazione dei boschi mediterranei.

1. Introduction

Forest habitats in the Mediterranean region are under significant threat from both natural events and human activities (Miranda et al., 2023; Rick et al., 2020). Extreme weather events and shifts in management practices hinder the attainment or maintenance of a favourable habitat conservation status (Cuttelod et al., 2008; Dieler et al., 2017). Within this framework, it is of primary importance to define and apply standardised systems for recognizing and classifying forest habitats and for the assessment of their conservation status. Some Member States defined criteria and indicators, either for forest habitats in general (Maciejewski, 2016), or specifically for each habitat (Pescador, 2019). However, this effort is lacking in other Member States. Gaps in knowledge limiting these activities include:

- lack of parameters and indicators for the conservation status assessment;

- lack of a regional list of the habitats' typical species;

- field-sampled information on forest habitats' multi-taxon biodiversity.

Overall, this translates into a pronounced need for concrete and shared transnational strategies for conserving and monitoring Mediterranean forest habitats.

The Life GoProFor Med project objective is to improve and/or maintain the conservation status of four specific forest habitats in the Mediterranean Biogeographical Region. This objective will be achieved through the implementation of flexible, close-to-nature management models in 12 sites within Natura 2000 areas across Italy, Spain, France, and Greece.

The Target Forest Habitats are:

9330 - *Quercus suber* (Cork Oak) Forests;

9340 - *Quercus ilex* and *Quercus rotundifolia* (Holm Oak and Portuguese Oak) Forests;

9260 - *Castanea sativa* (Sweet Chestnut) Woods;

9530* - (Sub-) Mediterranean Pine Forests with Endemic Black Pines.

These habitats are significant not only for their surface area but also for their sensitivity to management practices, which can threaten their conservation status.

The specific project objectives are:

(1) defining a system of recognition and classification of forest habitats common to the main countries within the Mediterranean biogeographical region;

(2) reinforcing the methods and indicators to evaluate the conservation status of the target habitats;

(3) sharing of strategies, techniques and actions necessary to improve the conservation status of the target habitats;

(4) identifying planning and forestry techniques adequate to reduce the risk of fire accounting for conservation strategies;

(5) defining and implementing easy-to-use tools for the habitat managers to apply and monitor the effects of silvicultural activities.

Task 2.1 aims at:

1. Testing and adapting current methods related to structure-based indicators, including TreMs, with sampling and analysis adapted to the Mediterranean habitats targeted by the project;

2. Verifying the effectiveness of TreMs as indicators of species diversity in key taxonomic groups, i.e., saproxylic arthropods and habitat diagnostic vascular plant species.

3. Contributing to sustainable forest management by using novel indicators and management strategies.

1.1 Target habitats

1.1.1 *Quercus suber* forests (9330)

These forests thrive in the western Mediterranean basin, particularly on acidic soils. Covering approximately 2.5 million hectares, they are valued for cork production and also provide grazing land, holding significant ecological and social functions (Aronson et al., 2009; Bugalho et al., 2011). Despite this, their conservation status is unfavourable or poor in several Member States (European Environment Information and Observation Network, 2025).

Threats include pests, diseases, and high-intensity fires. Notably, *Phytophthora cinnamomi* and drought, worsened by climate change, have caused significant declines (De Sampaio e Paiva Camilo-Alves et al., 2013). In Portugal alone, 15-20% of cork oak forests have burned since 1990 (Catry et al., 2012). While cork oaks are fire-tolerant, improper management and abandonment increase fire risks and habitat fragmentation, impacting ecosystem functions (Avila et al., 2016). Noteworthy, the abandonment of management practices may also determine relevant changes in the structure, function and composition of these ecosystems (Bensettiti et al., 2001; Micó et al., 2022).

1.1.2 *Quercus ilex* and *Quercus rotundifolia* forests (9340)

These forests are widespread in the Mediterranean region, growing on both calcicolous and silicicolous soils, in coastal and inland areas. Holm oaks (*Quercus ilex*) and Portuguese oaks (*Quercus rotundifolia*) are the dominant and characterizing species, which may either compose evergreen forests in warm climates, or mixed deciduous/evergreen forests in regions where the climate is closer to the one occurring in the temperate region. These forests have been crucial for human activities across the Mediterranean basin since the Neolithic era, supporting local economies through resources like fuel and agroforestry (Blondel & Aronson, 1999).

Despite their ecological importance in biodiversity conservation and soil erosion prevention, their conservation status is unfavourable or poor in many areas (European Environment Information and Observation Network, 2025). They face threats from extreme climate variations, poor management practices, and pathogens like *Phytophthora* root rot (*Phytophthora cinnamomi*) (Brasier, 1996). Drought, rising temperatures, and soil aridity are already affecting species composition and the persistence of these oak woodlands (Sánchez de Dios et al., 2009). Among the management practices affecting the habitat conservation status is frequent coppicing, and the general lack of biodiversity-relevant habitat structures.

1.1.3 *Castanea sativa* woods (9260)

These forests, dominated by chestnut trees, often include old plantations with semi-natural undergrowth. Traditionally managed orchards support diverse plant communities, including species of conservation interest (Conedera et al., 2004). Historically maintained for fruit and wood production through traditional practices, these semi-natural forests have drastically declined due to socio-economic changes and urban migration. In Italy, chestnut orchards have reduced by 90% since the early 20th century (Pezzi et al., 2020). The Article 17 web tool classifies their conservation status as unfavourable or poor in most Member States (European Environment Information and Observation Network, 2025) This habitat is threatened by abandonment, exacerbated by pests such as the chestnut blight (*Cryphonectria parasitica*) (Anagnostakis, 2001). However, intensive management practices, such as conversion to coppices, harm forest structure and lead to the loss of veteran trees essential for certain organisms (Mitchell, 2005). Effective conservation relies on moderate, continuous traditional management (Paillet et al., 2010).

1.1.4 (Sub-)Mediterranean pine forests with endemic black pines (9530*)

These forests, primarily composed of black pines (*Pinus nigra*), are found in montane-Mediterranean regions. Despite their critical ecological and genetic value, their conservation status is unfavourable due to the escalating impacts of climate change, including increased fire risk, drought, and pest infestations (Ojeda 2020). Challenges also arise from inadequate post-fire regeneration and the management practices applied in plantations, both posing significant threats to the habitat conservation value (Rigling et al., 2013).

1.2 Monitoring forest biodiversity in Europe

Expectations, targets, and progress in Sustainable Forest Management (SFM), including innovative management methods and best practices, are comprehensively defined and articulated through agreed Criteria and Indicators (C&I). These are applied globally, regionally, nationally, and locally. Each criterion refers to a sustainability aspect and is represented by one or more measurable indicators. These indicators monitor forest status and changes quantitatively, qualitatively, and descriptively (Forest Europe, 2020). Indicators of SFM are developed through three main processes:

1. <u>Reviewing existing forest data:</u> Utilizing current data sets to establish baseline conditions and trends (Fig. 1);
2. <u>Stakeholder engagement:</u> Engaging various stakeholders to prioritise performance aspects of the forest sector;
3. <u>Alignment with international C&I:</u> Ensuring compatibility with international standards and practices (Linser & O'Hara, 2019).

National Forest Inventories (NFI) were chosen as the primary tool for developing nationwide SFM indicators (Simons et al., 2021). They are widely accessible and originally designed to assess wood growing stock and production, despite not fully indicating international sustainability criteria. At the European level, NFI data, aggregated and published every five years for over three decades, offer indicators for sustainable forest management (Forest Europe, 2020). The Criterion 4 focuses especially on biodiversity maintenance, conservation, and enhancement, and should guide decision-makers towards biodiversity-friendly forest management in European forests.

However, the concrete reliance on biodiversity sustainability indicators remains a challenge, since most of the currently used indicators are indirect biodiversity proxies based on NFI or land cover maps. Only two indicators (*Threatened forest species* and *Common forest bird species*) involve species other than trees. This reliance on habitat attributes and area-based metrics simplifies data collection but certainly overlooks relevant ecological processes (Marshall et al., 2020). Despite NFI's extensive use for biodiversity assessment, the lack of direct links with forest biodiversity is largely recognised (Gao et al., 2015; Paillet et al., 2018; Storch et al., 2023; Zeller et al., 2022). In addition to the data that may be retrieved from NFI, i.e., stand structure and deadwood, recently additional indicators based on the occurrence of specific habitat structures that may represent or indicate the occurrence of a component of the habitat of organisms across multiple taxonomic groups are being inventoried, quantified and tested, such as Tree-related Microhabitats (TreMs) and Index of Biodiversity Potential (IBP). Several research efforts aimed at investigating the potential, propose specific classifications, identify drivers or means of implementation, and validate these indicators (Asbeck et al., 2021), with a relatively smaller body of literature focusing of the most recent approaches, i.e., TreMs and IBP (Fig. 1).

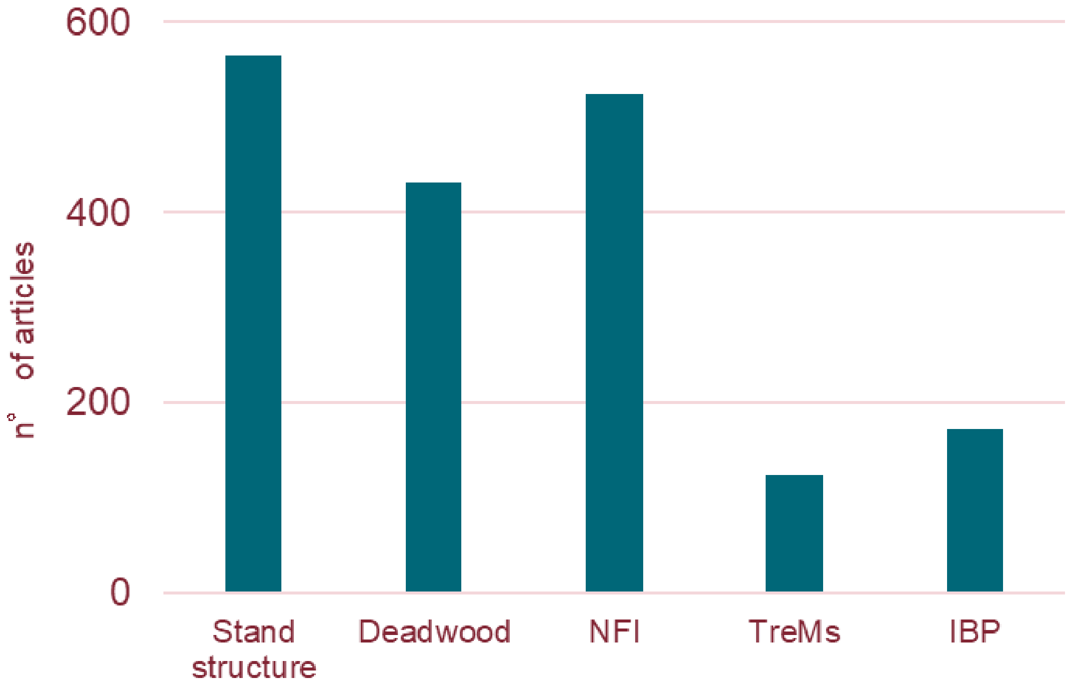

Figure 1. Number of articles in the Web of Science (https://www.webofscience.com/) focused on forest biodiversity and different types of structural indicators. The articles included in the count were those responding to the queries TS= (forest biodiversity AND indicator AND from left to right: (stand structure OR stuctural attribute* OR structural characteristic*)); (tree-related microhabitat* OR TreM* OR tree related microhabitat*)); (forest inventor* OR NFI*)); (deadwood OR dead wood OR woody debris OR CWD)); (index of biodiversity potential OR Indice de biodiversité potentielle) reported for countries within the Pan-European region.

Notwithstanding the above-mentioned body of literature, the links between these structure-based indicators and the diversity of species within a forest were often found to be weak or absent (Lassauce et al., 2011; Paillet et al., 2024; Sabatini et al., 2016).

1.3 Tree-related microhabitats (TreMs)

A TreM is a distinct, well delineated structure occurring on living or standing dead trees, that constitutes a particular and essential substrate or component of the habitat for species or communities (Larrieu et al., 2018b). TreMs are above-ground tree morphological singularities and, as such, do not occur neither on all trees in a forest, nor on all trees of the same species, e.g., rough bark on oak or larch. TreMs encompass both tree-originating modifications caused by biotic and abiotic impacts, such as intrusions, lesions and breakages, which expose sap and heartwood and initialise outgrowth structures and wood decay, as well as elements of external origin that are physically linked to the tree. TreMs are explicitly restricted to above-ground structures on standing trees, thus excluding similar structures occurring on lying deadwood (Asbeck et al., 2021; Larrieu et al., 2018a, 2018b).

While TreMs occur naturally on large old trees, in managed forests trees are often harvested before reaching this age phase. For this reason, understanding the presence of tree-related microhabitats and implementing tailored management practices to preserve and promote them has gained relevance to enhance forest biodiversity within at the local scale (Asbeck et al., 2021).

The relevance of Tree-Related Microhabitats (TreMs) as biodiversity indicators in central European temperate forests is underscored by their widespread adoption in integrative conservation concepts. Institutions, federal states, and certification schemes in countries like Germany, Austria, Switzerland, and France use TreMs as criteria for selecting habitat trees (Bütler et al., 2013, 2021). Habitat trees are old live or dead trees that provide ecological niches like cavities, bark pockets, dead branches, epiphytes, cracks, sap runs, or trunk rot. These concepts have evolved to systematically include legally protected habitats such as large vertebrate nests, woodpecker cavities, and microhabitats crucial for invertebrates (Bütler et al., 2020; Lachat et al. et al., 2013; Ranius et al., 2008), Recommendations often focus on identifying individual trees or small groups that exhibit TreMs, ensuring their retention in forest management practices aimed at biodiversity conservation (Bütler et al., 2013, 2021; Müller et al., 2019). The selection criteria typically encompass specific features like rot holes, sapwood or heartwood exposures, and saproxylic fungi fruiting bodies, although newer guidelines in regions like BadenWürttemberg and Graubünden consider a broader array of TreM types (Bütler et al., 2021). These practices are particularly relevant in older forest stands undergoing harvesting, aiming to preserve five to ten habitat trees per hectare, prioritizing trees with unique dimensions, shapes, or species characteristics (Asbeck et al., 2021; Bütler et al., 2013, 2021; Ranius et al., 2008).

The TreM typology for temperate and Mediterranean forests, outlined by Larrieu et al. (2018a, 2018b) delineates 15 groups of TreMs across seven forms, including:

- Cavities (CV): woodpecker breeding cavities, rot holes, concavities, insect galleries, and bore holes;
- Tree injuries and exposed wood (IN): exposed sapwood and/or exposed heartwood;
- Crown deadwood (DE);
- Excrescences (EX): twig tangles (witches broom), cankers, and burrs;
- Fruiting bodies of saproxylic fungi and slime molds (FU): perennial and ephemeral fungi fruiting bodies;
- Epiphytic, epixylic, and parasitic structures (EP): epiphytic crypto- and phanerogams, nests of vertebrates and invertebrates, micro-soil;
- Fresh exudates such as sap run and heavy resinosis (ES).

1.4 Index of Biodiversity Potential (IBP)

The Index of Biodiversity Potential (IBP) serves as a tool for evaluating the biodiversity potential of specific forest areas (Larrieu & Gonin, 2008). It considers various factors influencing ecosystem biodiversity, such as natural habitat presence, plant and animal species diversity, habitat quality, and other ecological parameters based on 10 factors:

A. Tree richness;
B. Vertical structure;
C. Standing deadwood;
D. Lying deadwood;
E. Very large trees;
F. Habitat-trees;

G. Openness;

H. Temporal continuity of the woody state;

I. Wet macrohabitats;

J. Rocky macrohabitats.

Typically used in environmental assessments, landscape planning, and biodiversity conservation, the IBP helps identify ecologically valuable areas that require special attention in management and conservation efforts.

Recently, an attempt to test the links between the values of this index with the species richness of spiders, bats, birds, bryophytes, carabids, fungi, true bugs, lichens, moths, necrophagous beetles, phytophagous beetles, plants, and saproxylic beetles was made based on data from German forests (Zeller et al., 2022). Among the investigated taxonomic groups, the IBP is positively correlated with species richness of birds, fungi, true bugs, lichens, and moths, with relatively high coefficients.

Notwithstanding these results, it is essential to recognise that both the calculation of the IBP and its links to forest species diversity may vary depending on the environmental context, as well as on the conservation objectives; therefore, its interpretation and usage should align with local conditions and conservation needs.

2. Methods

2.1 Project sites

The study area encompasses four Mediterranean-climate countries in Europe: Italy, Spain, France, and Greece (Fig. 2). The investigated forest communities correspond to forest habitats listed in Annex I of the Habitats Directive 92/43/EEC, which are primarily associated with the Mediterranean Basin:

- Habitat 9330: *Quercus suber* forests, commonly known as cork oak forests.
- Habitat 9340: *Quercus ilex* and *Quercus rotundifolia* forests. These two species are morphologically similar and genetically related, commonly referred to as holm oak forests.
- Habitat 9260: *Castanea sativa* forests, commonly known as European chestnut forests.
- Habitat 9530*: (Sub-) Mediterranean pine forests with endemic *Pinus nigra*, commonly known as black pine forests.

All the sampling areas are part of the European Natura 2000 network and are located within Special Areas of Conservation (SAC). More information about the Natura 2000 network can be found on the Ministry of the Environment and Energy Security's Natura 2000 webpage (https://www.mase.gov.it/pagina/rete-natura-2000).

Depending on the target of interest, different biodiversity samples were taken. In this case we sampled vascular plants, epiphytic lichen species and saproxylic and phytophagous arthropods for the biodiversity survey; deadwood and tree-related microhabitats for the forest survey (Burrascano et al., 2021).

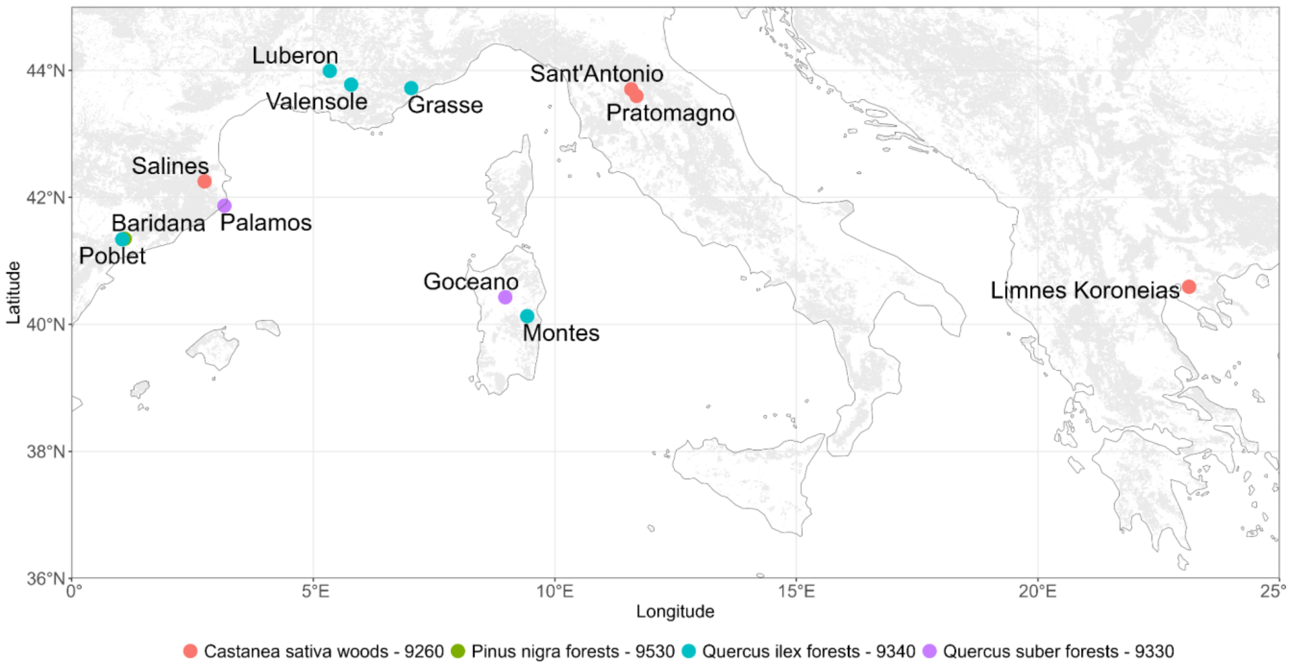

Figure 2. Study area with study sites. Habitat type 9260 (*Castanea sativa* forests) in red, habitat type 9340 (*Quercus ilex* and *Quercus rotundifolia* forests) in light blue, habitat type 9330 (*Quercus suber* forests) in purple. Habitat type 9530 (Sub-Mediterranean *Pinus nigra* forests) occurs only in Poblet (Spain), very close to the *Quercus ilex* site (the green dot is hidden by the blue one).

2.2 Biodiversity sampling

2.2.1 Vascular plant sampling

Vascular plants, such as trees, shrubs, and herbs, are the most frequently sampled taxonomic group in forests. This group is particularly suited for assessing forest biodiversity because it provides the physical structure for other organisms, constitutes the majority of forest primary productivity, and plays a crucial role in nutrient cycling. Vascular plants include a large number of habitat specialists distributed across broad environmental gradients, which are used to detect forest habitat diversity.

Each vascular plant species was recorded along with its estimated cover (%) inside 15x15 m square plots (Fig. 3). Square sampling units have the advantage of allowing for an accurate delimitation of the sampling unit through a measuring tape starting from the coordinates of a vertex.

We recorded separately species and abundance values for each of the three layers that are usually identified in European forests: overstorey, height greater than 3 meters; shrub, height between 1 and 3 meters; understorey, height below 1 meter.

	Vascular plants
Target taxonomic level	Species/species aggregate
Plot shape	Square
Plot size	15x15 m (225 m²)
Type of elements within the plot	-
Abundance score	Percentage cover for each species in each layer
Time needed (min.)	30-60/plot
Number of visits and season	1/year, early summer
Persons needed	1
Experts needed	1
Equipment costs (€)	<100

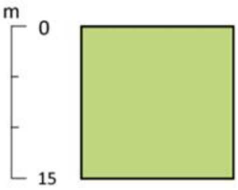

Figure 3. Vascular plants sampling unit and protocol.

2.2.2 Epiphytic lichens sampling

Although they have limited biomass, lichens play a vital role in forest ecosystems by supporting numerous ecological functions. Specifically, forest lichens help regulate the nitrogen cycle, provide shelter and hunting grounds for small invertebrates, and control temperature and water availability on epiphytic and epilithic surfaces. Rare epiphytic lichens are frequently found in specific microhabitats of old trees and other ancient forest structures, such as standing and fallen deadwood. Due to their unique biological characteristics and their presence in various forest ecological niches, lichens are excellent indicators of environmental conditions.

For each plot (15x15m), epiphytic lichens were sampled on 3 living trees (Fig. 4). For each tree trunk, four 10x50 cm sampling grids (each split into 5 10x10 cm quadrats) were located parallel to each trunk, at the four cardinal directions, between 100 and 150 cm from the ground (Fig. 5). If, within a plot, standing trees with biodiversity relevant features occur, e.g., over-mature/dying trees, sporadic tree species, trees close to forest gaps, etc., these were sampled to allow the detection of rare lichen species.

	Epiphytic lichens
Target taxonomic level	Species or morpho-functional groups
Plot shape	Square
Plot size	15x15 m
Type of elements within the plot	grid (5 quadrats) -> living trees
Number of elements	3 living trees
Element size	10x50 cm -> living trees
Abundance score	Frequency in standard sampling grids
Time needed	30-90/plot
Number of visits and season	1/year, no seasonality
Persons needed (min.)	1
Experts needed	1
Equipment costs (€)	<100

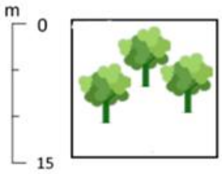

Figure 4. Epiphytic lichens sampling unit and protocol.

Figure 5. Lichens sampling grids (10x50 cm).

2.2.3 Saproxylic arthropods sampling

The study aims to investigate saproxylic arthropods inhabiting selected wooden logs lying on the ground. Saproxylic species depend on deadwood for at least one stage of their life cycle and represent a significant portion of the biodiversity associated with it (Stokland et al., 2012). Invertebrate saproxylic communities change over time according to the decomposition stage of the wood, along with its physical and chemical state (Parisi et al., 2018), and contribute significantly to wood degradation. Different tree species host specific saproxylic communities. Their degree of specialisation varies based on the decomposition stage. All arthropods residing in the logs were collected, preserved in vials containing pure ethanol, and identified to the species level using an integrative taxonomic approach.

In each plot, three logs (30-50 cm in length, 10-15 cm in diameter) were selected based on their decay class (one each from classes 2, 3, and 4). Preference was given to logs under partial or full tree cover. The logs were manually dissected using carpenter tools to collect all arthropods (larvae, pupae, and adults) present. Arthropods were gathered with entomological tweezers and mouth aspirators, then stored in test tubes filled with pure ethanol. Each tube was labeled with a unique code detailing the country, region, plot code, collection round, collection date, tree species (if available), and decay class. In the laboratory, the specimens were separated and placed in individual test tubes.

2.2.4 Phytophagous arthropods sampling

The study also examined phytophagous arthropods. Phytophagous arthropods represent a taxonomically diverse ecological group including moths and butterflies (Lepidoptera), beetles (Coleoptera), true bugs (Hemiptera), flies (Diptera), and grasshoppers and crickets (Orthoptera). Some of these groups are specialised to feed on specific host plants, while others are capable of feeding on a wide range of plant species. The diversity and abundance of phytophagous insects within forest ecosystems make plant-insect interactions a key factor in forest productivity and nutrient cycling (Kotze et al., 2022). The sampling was carried out along a diagonal (21 metres) within a square plot, oriented in a northeast direction. The three vegetation layers (herbaceous, shrub and tree) were struck with a stick up to a height of 3 m, causing the insects to fall onto a white sheet (1.5 x 1.5 m). Each arthropod specimen was then collected with entomological tweezers and then stored in test tubes filled with pure ethanol. This procedure was repeated for each vegetation layer. Each test tube was labeled with a site code, plot code, vegetation layer and plant species. In the laboratory, the samples were separated and placed in individual test tubes.

2.2.5 Birds and bats sampling

Bats and birds were sampled at 12 project sites, within two survey areas: one in the core area and the other in the edge/intervention area. Data were collected using acoustic recordings simultaneously at the two survey areas for 48 hours, one per month. The activity of birds and bats was calculated by dividing the total number of passes by the total number of recording hours at each survey point.

Since not all bats can be identified to the species level by their acoustic vocalisations, the species were aggregated into specific acoustic groups based on similar fonograms.

2.3 Stand structure sampling

Trees were sampled across circular areas of about 15 meters in diameter (Fig. 6). Inside each plot, the measured trees were numbered using enamel paint. If possible, numbering the trees started from the central tree, with subsequent numbers facing the center of the plot.

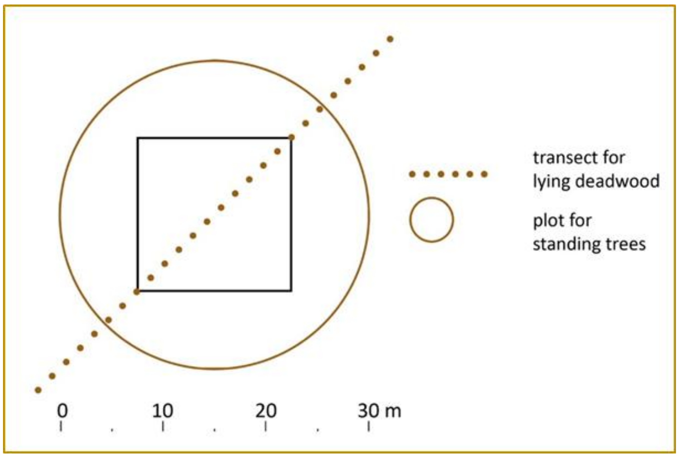

Figure 6. Plot for standing trees and deadwood standing trees.

2.3.1 Deadwood

In each sampling plot we examined dead standing trees (diameter > 10 cm), snags (diameter > 10 cm, height > 1.3 m) and stumps (diameter > 10 cm, height < 1.3 m). We conducted species identification and decay class assignment (Fig. 7) for each deadwood unit. For each snag we measured DBH (diameter at breast height) at 1.35 m from the highest point of the ground at the tree base and the height. For each stump, both top and bottom diameters, as well as height and the origin of the stumps, were recorded or estimated.

The decay classes were established following Harmon et al. (2011), considering five classes. These are the same classes used in the Field guide to tree-related microhabitats (Bütler et al., 2020).

<u>Decay classes for standing dead trees:</u>

- Class 1: All limbs and branches are present; the top of the crown is still present; all bark remains; sapwood is intact, with minimal decay; heartwood is sound and hard.
- Class 2: There are few limbs and no fine branches; the top may be broken; a variable amount of bark remains; sapwood is sloughing with advanced decay; heartwood is sound at the base but beginning to decay in the outer parts of the upper bole.
- Class 3: Only limb stubs exist; the top is broken; a variable amount of bark remains; sapwood is sloughing; heartwood has advanced decay in the upper bole and is beginning at the base.
- Class 4: Few or no limb stubs remain; the top is broken; a variable amount of bark remains; sapwood is sloughing; heartwood has advanced decay at the base and is sloughing in the upper bole.
- Class 5: No evidence of branches remains; the top is broken; <20 percent of the bark remains; sapwood is gone; heartwood is sloughing throughout.

<u>Decay classes for lying deadwood:</u>

- Class 1: Sound, freshly fallen, intact logs with no rot, no conks present indicating a lack of decay, original color of wood, no invading roots, fine twigs attached with tight bark.

- Class 2: Sound log, sapwood partly soft but cannot be pulled apart by hand, original color of wood, no invading roots, many fine twigs are gone and remaining fine twigs have peeling bark.
- Class 3: Heartwood is still sound with pieces supporting its own weight, sapwood can be pulled apart by hand or is missing, wood color is reddish-brown or original color, roots may be invading sapwood, only branch stubs are remaining which cannot be pulled out of the log.
- Class 4: Heartwood is rotten with piece unable to support own weight, rotten portions of piece are soft and/or blocky in appearance, a metal pin can be pushed into heartwood, wood color is reddish or light brown, invading roots may be found throughout the log, branch stubs can be pulled out.
- Class 5: There is no remaining structural integrity to the piece with a lack of circular shape as rot spreads out across ground, rotten texture is soft and can become powder when dry, wood color is red-brown to dark brown, invading roots are present throughout, branch stubs and pitch pockets have usually rotten down.

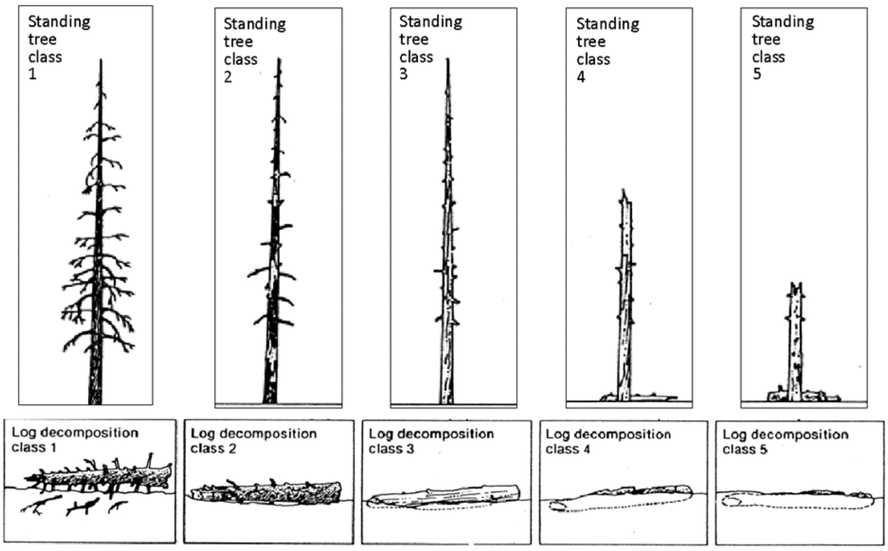

Figure 7. Deadwood decay classes for standing and lying fragments from McComb and Lindenmayer (1999).

2.3.2 TreMs survey

For each standing tree, the presence of tree-related microhabitats was observed and recorded using the categories and the codes referring to each specific microhabitat, also evaluating the size limits. For their description, size limits and macro-categories we followed Bütler et al. (2020):

- Cavities (CV): Woodpecker breeding cavities; Rot-holes; Insect galleries; Concavities.
- Tree injuries and exposed wood (IN): Exposed sapwood only; Exposed sapwood and heartwood.
- Crown deadwood (DE).
- Excrescences (EX): Twig tangles; Burrs and cankers.
- Fruiting bodies of saproxylic fungi and slime moulds (FU): Perennial fungal fruiting bodies; Ephemeral fungal fruiting bodies and slime moulds.
- Epiphytic and epixylic structures (EP): Epiphytic and parasitic crypto- and phanerogams; Nests; Microsoils.
- Exudates: Fresh exudates (ES).lc

2.3.3 IBP assessment

The IBP may be measured at the stand or stand type level using different survey methods: the simplest is the complete coverage method, where the entire stand is uniformly surveyed along regularly spaced transects using GPS in trace mode. Observations are made on strips typically 10-20 meters wide on either sides of the transect axis, ensuring no double counting between neighboring surveyors or adjacent strips. This method is suitable for small stands (less than 5 hectares).

For the present project, however, a partial coverage survey was adopted. It surveys a representative fraction of the stand such as every other strip, with rapid additional surveys in non-sampled areas. The IBP score is determined based on observations from the sampled areas.

From the start of the survey, we recorded all necessary elements such as tree species and deadwood. Data is collected through careful visual estimation rather than exhaustive inventory, ensuring precision in identifying elements necessary for IBP assessment. The percentage of cover for different categories, e.g., native tree species, is estimated by calculating the ground-projected area in square meters in relation to the stand area.

Standardise search effort to avoid overestimation, typically setting a maximum survey duration of 15-20 minutes per hectare per person, which may extend to 25-30 minutes in more difficult conditions. Preparation and data processing times must also be considered.

2.3.4 Canopy photography

For each plot, nine photographs were taken using a DSLR camera mounted on a tripod, positioned at a 90° angle with the base leveled horizontally (Pekin & Macfarlane, 2009). The photographs were processed and analyzed using the R package "coveR" (Chianucci et al., 2022), which follows the methodology of Macfarlane et al. (2007). This approach calculates various canopy metrics such as total cover, Leaf Area Index (LAI), and canopy gaps.

Images were converted to binary values (0-1) based on the contrast between canopy and sky pixels. Pixels representing the sky were assigned a value of 1, while those representing canopy were assigned 0. Gaps were classified by size, with large gaps defined as covering ≥1.3% of the image, and small gaps as <1.3% (Macfarlane et al., 2007; Pekin & Macfarlane, 2009). After classification, several canopy structural indices were calculated using the following equations:

- **Gap Fraction (GF):** Proportion of sky pixels in the image.

  $$GF = \frac{gT}{NR}$$

  where gT is the number of sky pixels, and NR is the total number of pixels.

- **Foliage Cover (FC):** Complement of the gap fraction.

  $$FC = \frac{1}{GF}$$

- **Crown Cover (CC):** Complement of the large gap fraction.

  $$CC = 1 - \frac{gl}{NR}$$

  where gLgLgL is the number of large gap pixels.

- **Crown Porosity (CP):** Fraction of small gaps within the canopy

$$CP = 1 - \frac{FC}{CC}$$

- **Leaf Area Index (LAI):** Calculated using the formula:

$$L = -CC \cdot (log \frac{(CP)}{k})$$

where k=0.5 is the extinction coefficient.

2.4 Statistical analyses

In order to link the various structural parameters and indicators described in the previous sections, we modeled the response of different taxonomic groups to the total abundance of TreMs sampled in each plot, the number of TreM types found in each plot and the total IBP. We added to these indicators some structural variables that may be relevant to guide management strategies implemented within the framework of the project or in general for the target habitats.

The response variables were different across taxonomic groups:

- Vascular Plants - Cover of habitat diagnostic species;
- Epiphytic Lichens - Shannon index based on species frequency;
- Saproxylic Arthropods - Number of functional groups.
- Phytophagous Arthropods - Number of functional groups.
- Birds - species richness and Shannon index based on species frequency;
- Bats - species richness and Shannon index based on acoustic groups frequency;

The calculation of each of these variables required specific methodologies and for each of them a specific set of explanatory variables were selected.

1. Vascular Plants: For the diagnostic species, we have included all the plant species of the herbaceous layer (height of individuals < 1m) and the shrub layer (height of individuals between 1m and 3m) that are listed in at least one of the four habitat interpretation manuals of the countries involved. We then summed the percentage cover of these species within each plot and divided it for the sum of the cover of all species in the same plot, therefore obtaining the relative cover of diagnostic species. The response variables for this first model were:
    - Site: the site column indicates the location of each sampling unit, reflecting geographical, environmental, and management differences.
    - Canopy Cover (CC): calculated following the methodology described by Chianucci and Macek (2023), using hemispherical canopy photographs taken during the peak vegetative season. In this study, nine canopy photos were taken per sampling unit and analyzed to estimate the percentage of canopy cover. This metric provides insights into the light availability and forest structure.
    - Total IBP Score: The Index of Biodiversity Potential (IBP) is a composite indicator that reflects the capacity of a forest to support biodiversity (Larrieu & Gonin, 2008).
    - Abundance of TreMs: This metric quantifies the total number of tree-related microhabitats (TreMs) observed per plot.

- Number of Types of TreMs: This variable measures the diversity of TreM types present within a plot, reflecting the range of habitat features available for different species.
- Basal Area Classes (BAXCD1 to BAXCD6): These variables represent the basal area (m^2/ha) of trees divided into six diameter classes, which provide detailed information on forest stand structure and size distribution. The basal area classes capture the contributions of different tree size categories to overall stand structure, which is essential for understanding habitat availability for species dependent on large trees or specific structural conditions:
  - BAXCD1: Basal area of trees with diameters between 7.5 cm and 17.5 cm.
  - BAXCD2: Basal area of trees with diameters between 17.6 cm and 27.5 cm.
  - BAXCD3: Basal area of trees with diameters between 27.6 cm and 37.5 cm.
  - BAXCD4: Basal area of trees with diameters between 37.6 cm and 47.5 cm.
  - BAXCD5: Basal area of trees with diameters between 47.6 cm and 57.5 cm.
  - BAXCD6: Basal area of trees with diameters >57.5 cm.

2. Epiphytic lichens: we calculated the Shannon index, which represents the community biodiversity at plot level, taking into account both the number of species found and their evenness. In this case, evenness considers the frequencies of the species, meaning that the index value will be higher when the species found have similar frequencies. The response variables for this model were the same used for vascular plants.

3. Saproxylic arthropods**:** were divided into six categories: Predators, Detritivores, Xylophages, Phytophages, Saprophages, and Polyphages. The assignment of each individual to a specific functional category was based on the association between the individual's family and the feeding habit of that family.
   - Site.
   - Total IBP Score.
   - Abundance of TreMs.
   - Number of Types of TreMs.
   - Basal Area Classes (BAXCD1 to BAXCD6).
   - Decay class: state of decay of the deadwood unit where the functional group was found, following section 2.3.1.
   - Diameter: diameter (cm) of the deadwood unit where the functional group was found.

4. Phytophagous arthropods**:** individuals were partitioned into functional groups based on the functional traits pertaining the behavior and feeding habits of the identified families. The individuals were divided into three main categories: Saprophages, Non-saprophages, and Polyphages. Each of these main categories was further divided into subcategories based on more specific feeding habits. Specifically, the Saprophages were divided into Zoosaprophages, Phytosaprophages, and Polysaprophages. The Non-saprophages were further divided into the categories Predators/Parasitoids, Mycophages, and Phytophages. Within the Phytophages category, additional subcategories (Xylophages, Phyllophages, Spermophages, and Anthophages) were recognised based on the plant region the phytophages tend to feed on. The response variables for this model were:
   - Site.
   - Canopy Cover (CC).
   - Shrub Cover (SC): percentage of ground area covered by shrubs in each sampling unit.

- Herb Cover (HC): percentage of ground area covered by herbaceous vegetation in each sampling unit.
- Total IBP Score.
- Abundance of TreMs.
- Number of Types of TreMs.
- Basal Area Classes (BAXCD1 to BAXCD6).

5. Birds: we calculated the species richness at the forest stand level and the Shannon index, which represents the community biodiversity at the forest stand level, taking into account both the number of species found and their evenness. In this case, evenness considers the frequencies of the species, assessed through the number of detections per hour, meaning that the index value will be higher when the species found have similar frequencies. The predictor variables were the following:
    - Total IBP Score.
    - Abundance of TreMs.
    - Number of Types of TreMs.
6. Bats: we calculated the species richness at the forest stand level and the Shannon index, which represents the community biodiversity at the forest stand level, taking into account both the number of species found and their evenness. In this case, evenness considers the frequencies of the species, assessed through the number of detections per hour, meaning that the index value will be higher when the species found have similar frequencies. The predictor variables were the following:
    - Total IBP Score.
    - Abundance of TreMs.
    - Number of Types of TreMs.

2.4.1 Boosted Regression Trees (BRTs)

We ran boosted regression trees (BRTs) for epiphytic lichens, vascular plants and phytophagous and saproxylic arthropods to assess the relationship between the response variable of each taxonomic/functional group and the predictor variables.

Boosted regression trees (BRTs) effectively model complex non-linear relationships, and enable reliable identification of relevant variables and interactions, with a strong predictive performance and robustness against overfitting, missing data, and collinearity (Elith et al., 2008). The model setting involves finding the optimal combination of four main parameters (number of trees, learning rate, tree complexity and bag fraction) to minimise predictive error: the number of trees refers to the total count of individual decision trees, influencing both predictive performance and model stability; the learning rate controls the contribution of each tree to the final model, providing a balance between accuracy and the risk of overfitting; tree complexity determines the maximum depth of each tree, affecting the model's ability to capture complex patterns in the data; and the bag fraction specifies the proportion of the training set randomly selected for each iteration.

We used the gbm.step function from the 'dismo' package (Hijmans et al. 2022) to test various BRT settings by combining different learning rates (0.001, 0.0025, 0.005), tree complexity values (2, 3, 5), and bag fraction values (0.5, 0.75), and assess the relative importance (sum up to 100%) of each explanatory variable (Elith et al., 2008). We used the Gaussian error distribution. We selected parameter combinations that resulted in models with over 1000 trees and evaluated their performance using three metrics, following the approach of Napoleone et al. (2021): (i) explained deviance (D^2), calculated as $D^2 = 1 - (\text{residual deviance}/\text{total deviance})$. This metric ranges from zero to one, where a value of one indicates a perfect fit, and is considered a generalisation of the traditional R^2 used in regression analysis (Mouchet et al., 2015; Stojanova et al., 2010); (ii) the cross-validated mean correlation coefficient (CV), which measures the average correlation between the training and test datasets; and (iii) self-statistics (SS), which assesses the correlation between predicted and observed values. These correlation metrics are commonly used to evaluate the efficiency of Boosted Regression Trees (BRTs) (Napoleone et al., 2021; Szymura et al., 2018).

2.4.2 Boxplots

The sampling design for both birds and bats, involving two sampling units per site (core and intervention areas), limited the scope of our analysis. With a total of 24 sampling units, it was not possible to perform BRTs for quantitative inference. Instead, we adopted a qualitative approach to explore trends in species diversity (species richness and Shannon index) across classes of investigated indicators, including the IBP, TreMs abundance, and TreMs diversity.

A boxplot is a graphical representation of data that displays its central tendency (median), variability (interquartile range), and potential outliers. The box shows the interquartile range (IQR), which contains the middle 50% of the data, while the horizontal line inside the box represents the median. Whiskers extend to the smallest and largest values within 1.5 times the IQR, and individual points outside this range are shown as outliers.

3. Results

3.1 Results for vascular plants

The analyses of vascular plant species composition in response to the aforementioned indicators accounted for the role of vegetation in defining the habitats' conservation status. With this aim we calculated the abundance of the diagnostic species included in the lists purposely produced for the project aims and thoroughly described in the report D.2.2 for the task 2.5 *Vegetation-based manual for the recognition and conservation state assessment of the target habitats*.

This relevant indicator of the habitat occurrence and conservation state was modeled against the aforementioned structure-based indicators to pursue two aims of primary relevance for the project ultimate goal:

1. Identify the structural conditions related to a favourable conservation status;
2. Validate TreMs and IBP as potential indicators of the habitat conservation status.

The first aim will provide support and insights for close-to-nature management of the target habitats, the second aim will validate the habitat's monitoring approaches.

The effect of the site, which also includes the differences across habitats, is the variable explaining most variance (Fig. 8). However, other structural variables resulted as importantly linked to the relative cover of diagnostic species. The habitat conservation state in terms of diagnostic species is maximised by a canopy cover greater than 50%, meaning that below this threshold the occurrence of eliophilous competitive species does not allow the full development of the habitat.

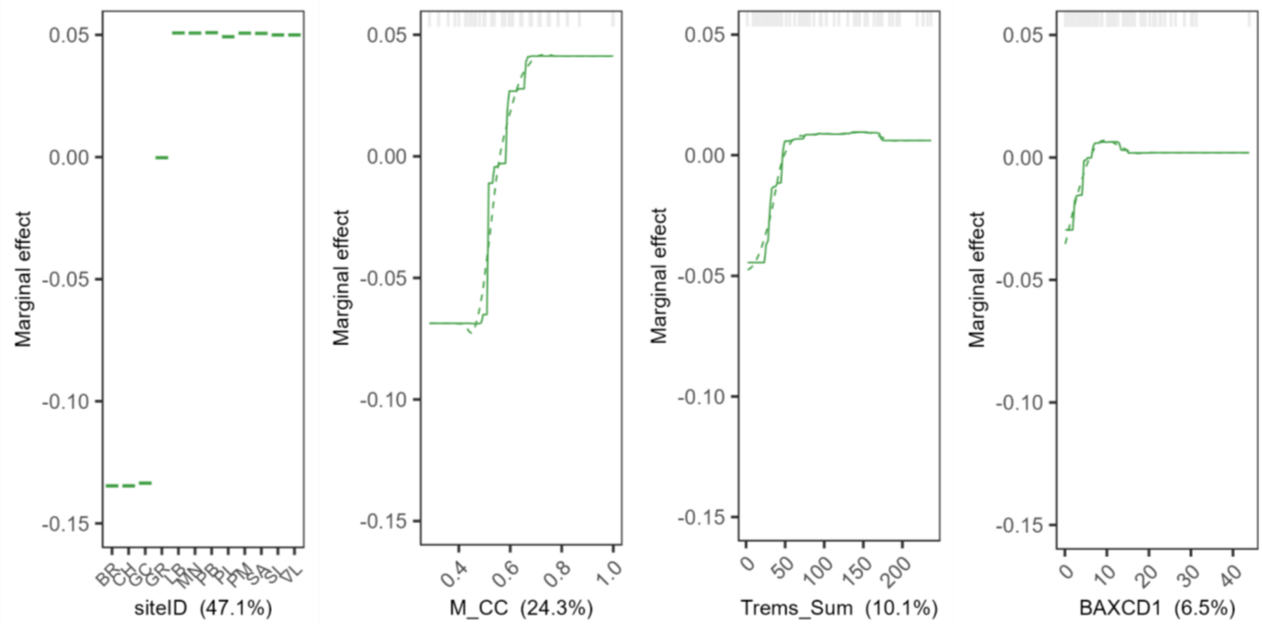

Figure 8. Partial dependence plots showing the marginal effect of site, canopy cover, abundance of TreMs, and basal area of the trees with DBH between 7.5 and 17.5 cm on the relative cover of diagnostic species. Grey stripes on the top of each graph represent the distribution of the data.

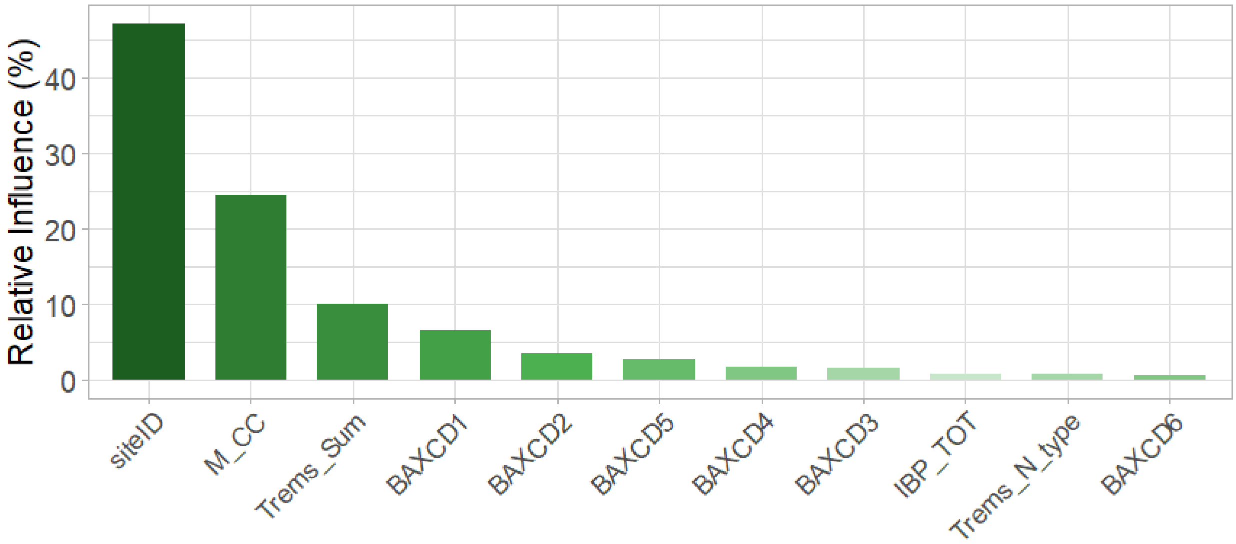

Figure 9. Relative influence of the predictor variables in determining the cover (%) of the diagnostic species of vascular plants per sampling unit according to BRTs.

Interestingly, the abundance of TreMs was more relevant that their diversity (Fig. 9), i.e., the number of types of TreMs represented. This means that the occurrence of a high number of TreMs of few specific types is relevant also for the habitat conservation state as assessed through the composition of the understorey. In particular, the most abundant TreMs in the sampled plots, thus those causing this link, are:

- Epiphytic and epixylic structures - Bryophytes, lichens, Ivy and lianas, ferns, mistletoe
- Crown deadwood - Dead branches, dead top, remnants of a broken limb
- Excrescences - Witches' broom and Epicormic shoots
- Tree injuries and exposed wood - Bark loss, fire scar, bark shelter, bark pockets
- Cavities - Insect galleries and bore holes.

These TreMs categories are in some cases abundant in those plots that are characterised by only a few types of TreMs, i.e., 1 to 4.

Some of these TreMs, when abundant, indicate the occurrence of a relevant number of senescent trees, e.g., crown deadwood and insect galleries, which are beneficial to the diversity of several taxonomic groups (Lindenmayer & Laurance, 2017). Others, like those related to epiphytic and epixylic structures may indicate a relatively high ecological continuity, which is also beneficial for forest biodiversity (Nordén et al. 2014).

Interestingly, also the basal area of the smallest diameter class (7.5-17.5 cm) higher than 10 m^2/ha is relevantly linked to the abundance of diagnostic species. This value of basal area is very low, and, as such, witnesses the relevance of the younger age classes to be represented within the target habitats.

Overall, the joint results on the abundance of TreMs related to senescing trees and on the smallest diameter class points to the relevance of maintaining a certain degree of uneven agedness at the stand scale.

3.2 Results for epiphytic lichens

Similarly to vascular plants, we included as explanatory variables for epiphytic lichens the variables related to canopy structure as well as dendrometric variables. Also in this case, the site had a great effect in explaining the changes in species diversity of epiphytic lichens. For this taxonomic group, however, a high tree density - especially in the diameter classes 7.5-17.5 cm and 27.5-37.5 cm, which are the most represented across the project sites - and a high degree of canopy closure have negative effects on this taxonomic group (Fig. 10).

Noteworthy, although less relevant, the abundance of TreMs showed positive links with the species diversity of epiphytic lichens (Fig. 11).

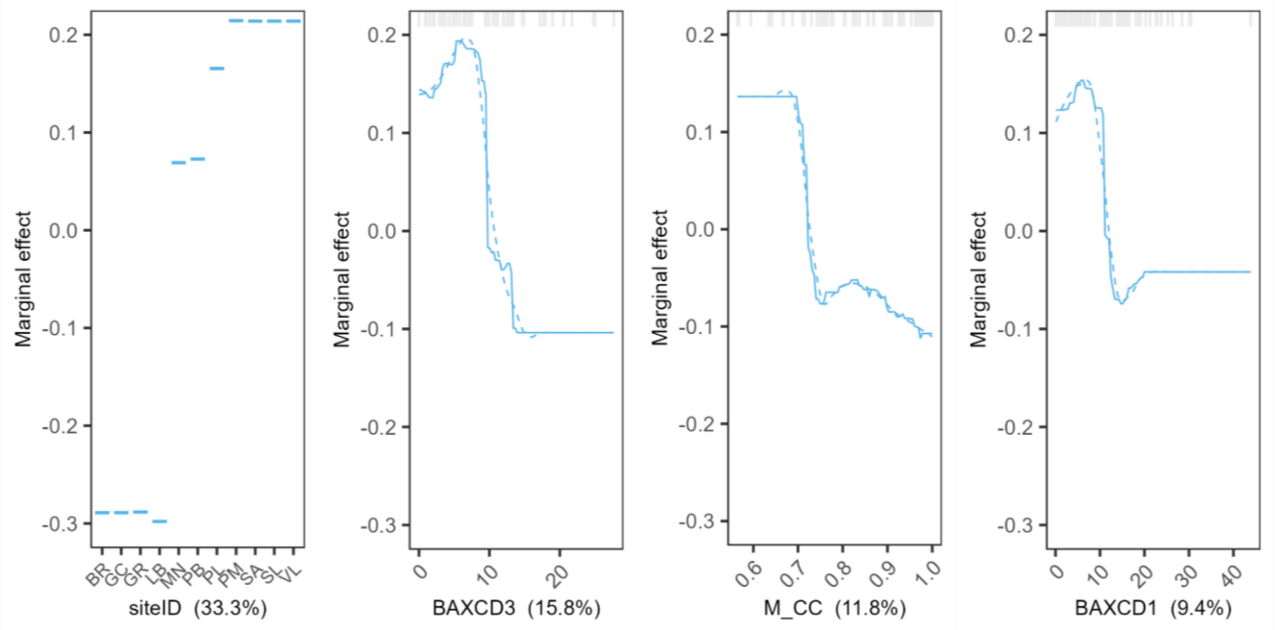

Figure 10. Partial dependency plots based on the Boosted Regression Trees modeling the Shannon index of epiphytic lichens against site, basal area of the trees with DBH between 27.6 and 37.5 cm., canopy cover, and basal area of the trees with DBH between 7.5 and 17.5 cm.

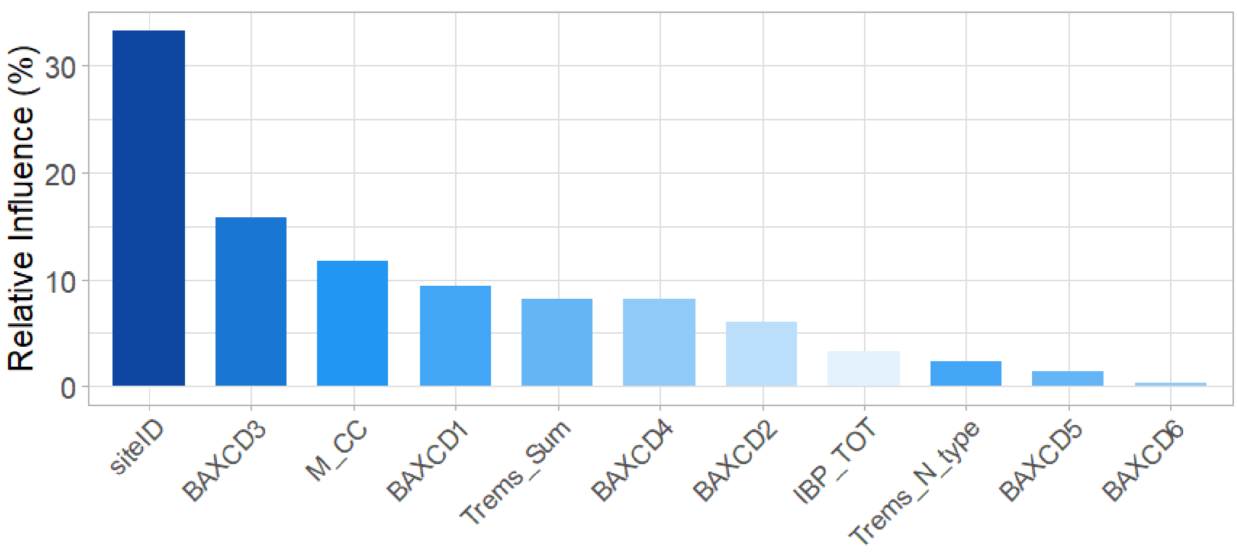

Figure 11. Relative influence of the predictor variables in determining the Shannon index of epiphytic lichens per sampling unit according to BRTs.

3.3 Results for saproxylic arthropods

For the saproxylic beetles, we accounted for structural variables related to deadwood, not at the level of plot or stand, but based on the size and quality of the individual deadwood fragment in which the arthropods were sampled. We included in our analysis the variables related to TreMs and the IBP.

Also for this group we found the abundance of TreMs to be relevant rather than their diversity (Fig. 13). Again, it is important to underline that this abundance variable mainly derives from the categories of TreMs mentioned for vascular plants linked to senescing trees. Surprisingly, in this case, the distribution of TreMs across different types has a general negative effect on the richness of functional groups, with an increase only over a certain number (five) of TreMs' types represented.

The IBP is positively linked to the diversity of saproxylic beetles functional groups with an inflection point for IBP values around 30, i.e., between 27 and 35 (Fig. 12). Based on our interpretation, these values were mainly found in the habitat 9340 *Quercus ilex* and *Quercus rotundifolia* forests, with low scores for the factors of the IBP related to openness and large living trees. This indicates that, even in areas where standing and lying deadwood occurs, the lack of gaps or a very high canopy closure may limit the diversity of saproxylic arthropods functional groups.

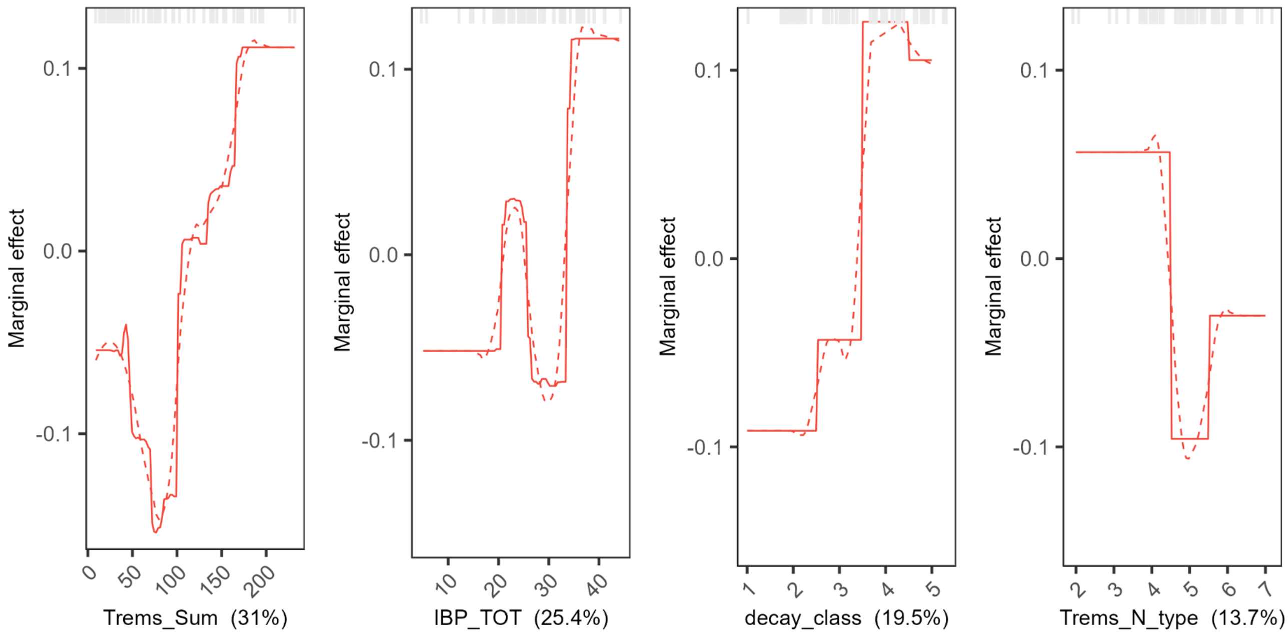

Figure 12. Partial dependence plots showing the marginal effect of abundance of Trems, total IBP score, decay class, and the number of types of Trems on the richness of functional groups of saproxylic arthropods. Grey stripes on the top of each graph represent the distribution of the data.

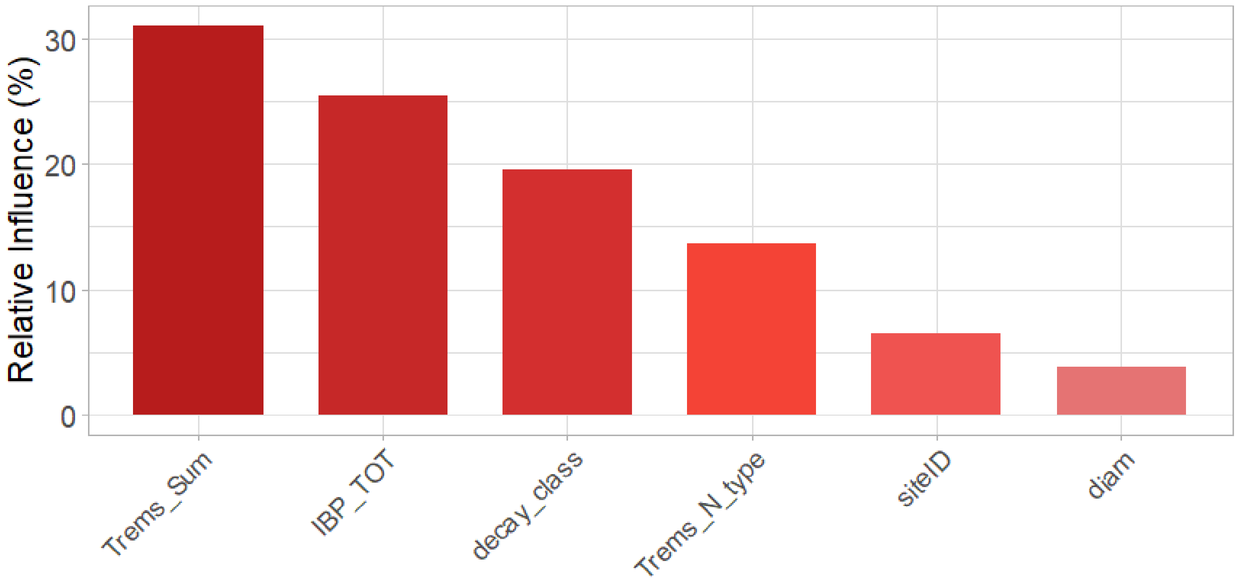

Figure 13. Relative influence of the predictor variables in determining the richness of functional groups for saproxylic arthropods per sampling unit according to BRTs.

3.4 Results for phytophagous arthropods

The results for phytophagous insects are partly in line with those for the other taxonomic groups. This group takes advantage of a lower density of trees in one of the most represented diameter classes (i.e., DBH between 27.6 and 37.5), and, accordingly, is favoured by a relatively high shrub cover, i.e., higher than 20%.

In this case the abundance of TreMs results as negatively related to the diversity of this group, however, this may be a spurious effect of the lower density of trees.

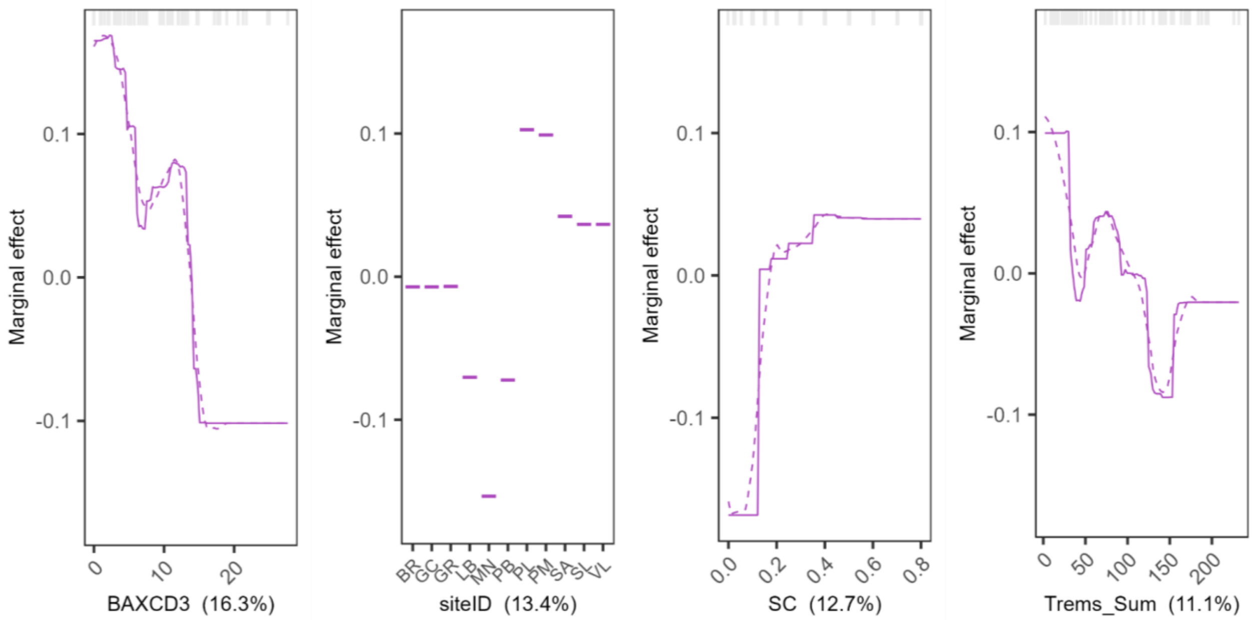

Figure 14. Partial dependence plots showing the marginal effect of basal area of the trees with DBH between 27.6 and 37.5 cm., site, shrub cover (%), and the abundance of TreMs on the richness of functional groups of phytophagous arthropods. Grey stripes on the top of each graph represent the distribution of the data.

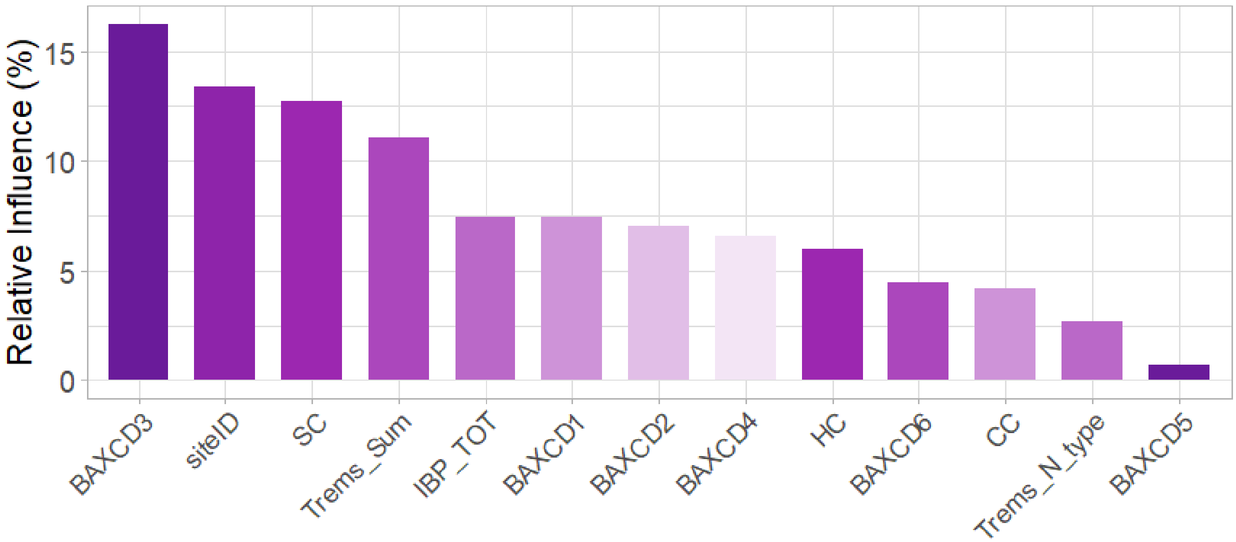

Figure 15. Relative influence of the predictor variables in determining the richness of functional groups for phytophagous arthropods per sampling unit according to BRTs.

3.5 Results for birds

The different sampling design for birds, encompassing two sampling units per site, one in the core and one in the intervention area, forced us towards a qualitative rather than quantitative analysis.

The overall size of the sample (24 sampling units) and its nested spatial structure (2 sampling units per site) did not allow modeling inference.

Therefore, for birds, we provide a visualisation of the distribution of species richness and Shannon index values across different classes of the investigated indicators, i.e., the IBP, the abundance and the diversity of TreMs.

Please note that we also subsetted the birds records for forest species and strictly forest species, and attempted the study of the relationships with overall IBP and TreM parameters as well as with specific TreM groups. However, none of these relationships was found to be meaningful.

3.5.1 IBP

The different IBP classes, from very low to very high values, are limitedly related to the richness of birds, with relatively high values in the only sampling units associated with a very high IBP value. However, the broad variability of species richness values in the other IBP classes hampered the possibility of identifying significant differences among these classes (Fig. 16).

Surprisingly, the general trend identified in terms of Shannon index is a decrease at increasing levels of IBP.

Since the Shannon index accounts for both species richness and evenness, this result, analysed jointly with the one for species richness, reveals that, if a link with IBP is to be found, this would derive from the contribution of non-abundant species to the species richness, since the bird community evenness is relatively low (Fig. 17).

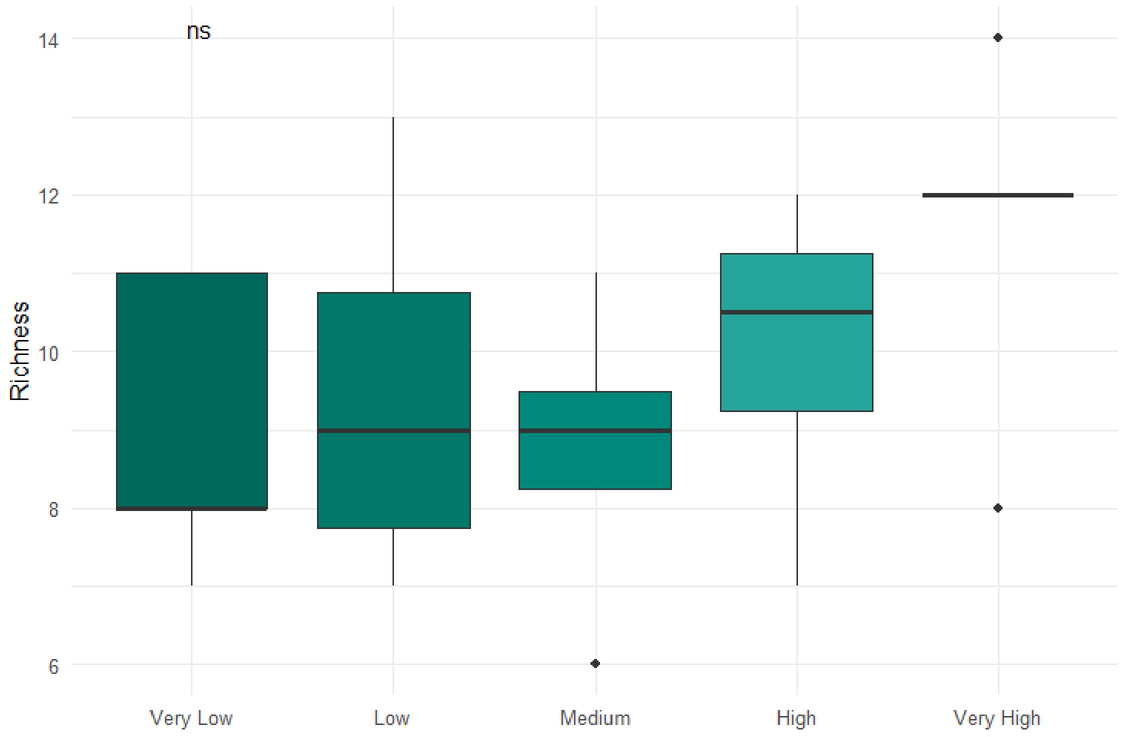

Figure 16. Bird species richness distribution across five classes of IBP.

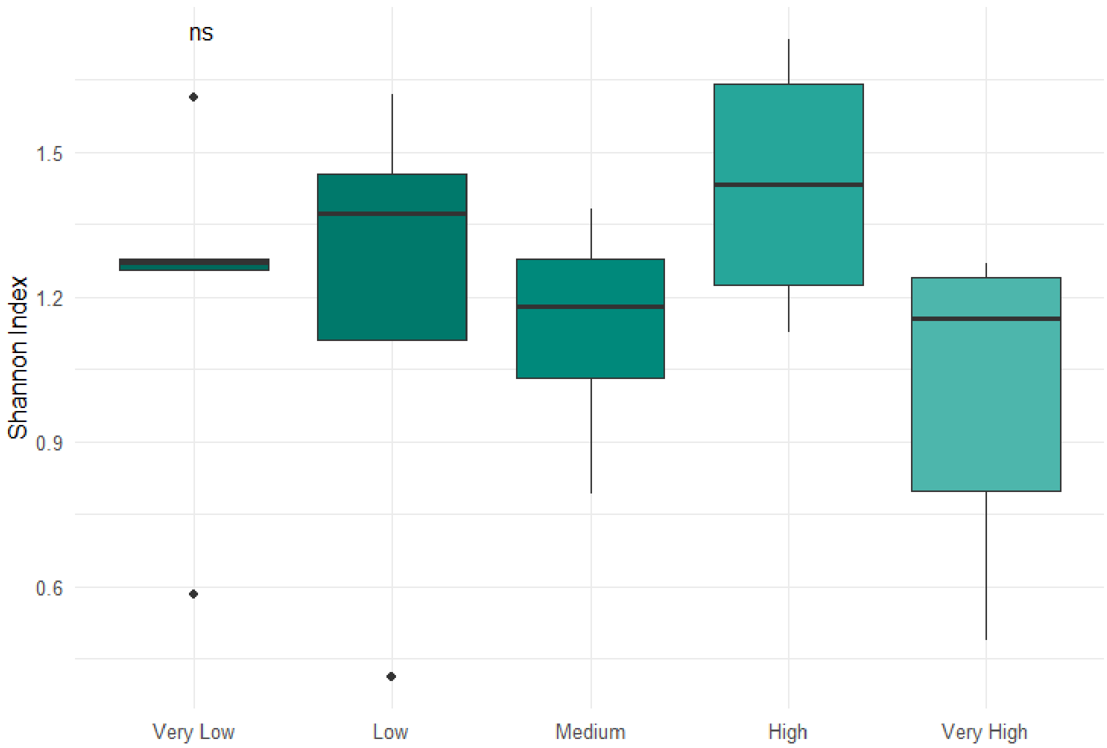

Figure 17. Bird Shannon species diversity distribution across five classes of IBP.

3.5.2 Abundance and diversity of TreMs

The distribution of species diversity values across classes of TreMs abundance and diversity did neither significant differences nor trends.

Notwithstanding the documented links between many bird species and TreMs, we were not able to identify a positive response in terms of bird species diversity.

This may not be attributed to bird communities dominated by generalist species in the sampled areas, since most of the species sampled were to some extent associated with forest habitats. Several woodpecker species, such as Great Spotted Woodpecker (*Dendrocopos major*), Black Woodpecker (*Dryocopus martius*), Iberian and Eurasian Green Woodpecker (*Picus sharpei* and *P. viridis*), as well as other forest-related species, such as Short-toed Treecreeper (*Certhia brachydactyla*), Eurasian Nuthatch (*Sitta europaea*), Coal Tit (*Periparus ater*), and the more generalist Eurasian Wren (*Troglodytes troglodytes*) were sampled in the project sites. However, whereas these species occurred in the vast majority of sampled sites, the cavities that may be linked to woodpecker nests, for instance, were found only in eight areas out of 24, meaning by area either the core or intervention areas in each site. Conversely, woodpecker feeding holes were found in 19 out of 24 areas. This means that, in the sampled sites, these species are relatively common, as well as some of the TreMs related to their occurrence, while other of these TreMs are rare, notwithstanding the species diffuse occurrence. As a result, no pattern emerges that links bird species diversity and TreMs' variables, neither TreMs' abundance (Fig. 18 and 19), nor TreMs' diversity (Fig. 20 and 21).

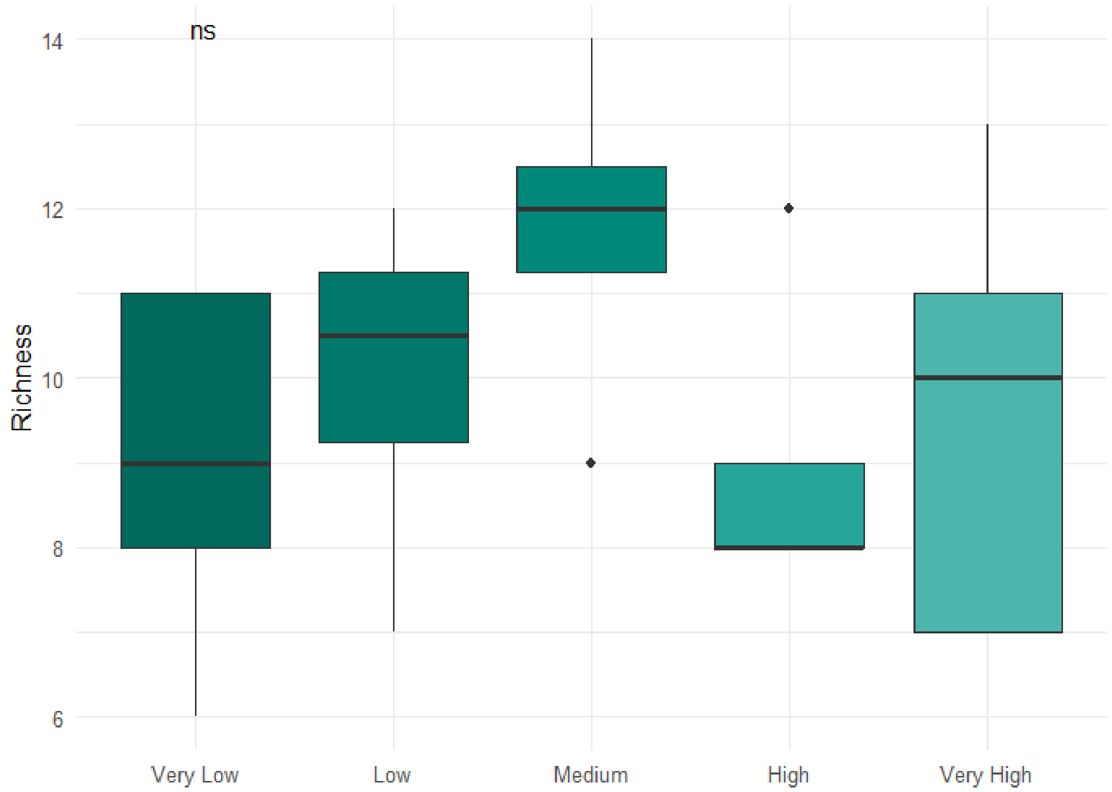

Figure 18. Bird species richness distribution across five classes of TreMs' abundance

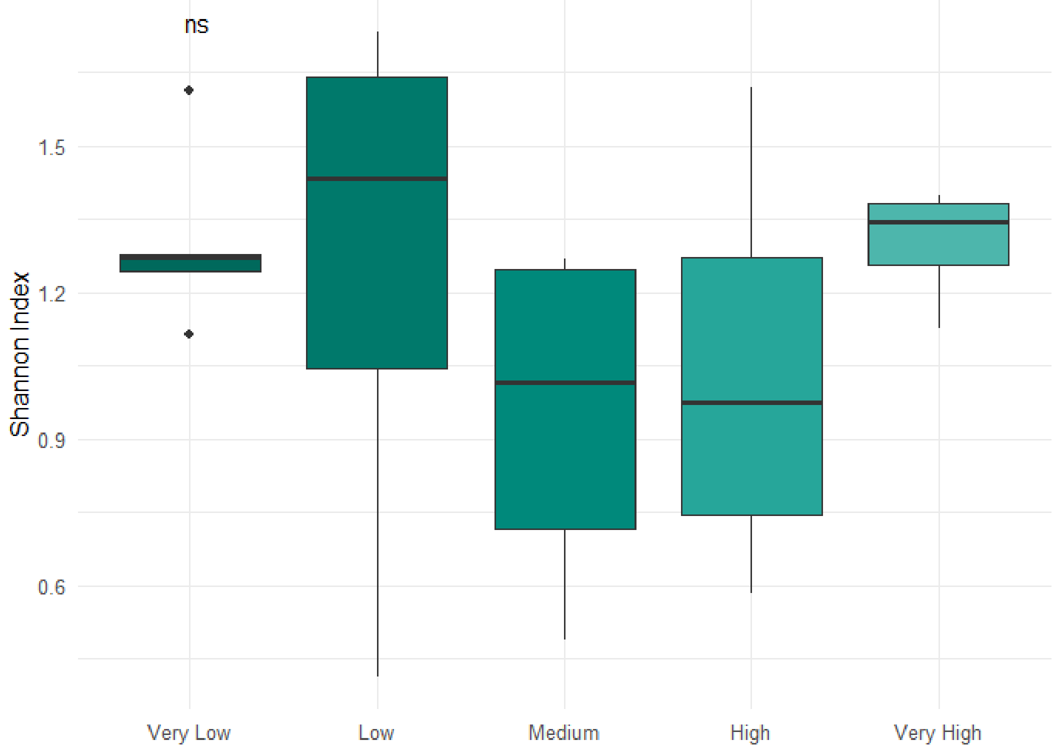

Figure 19. Bird Shannon species diversity distribution across five classes of TreMs' abundance

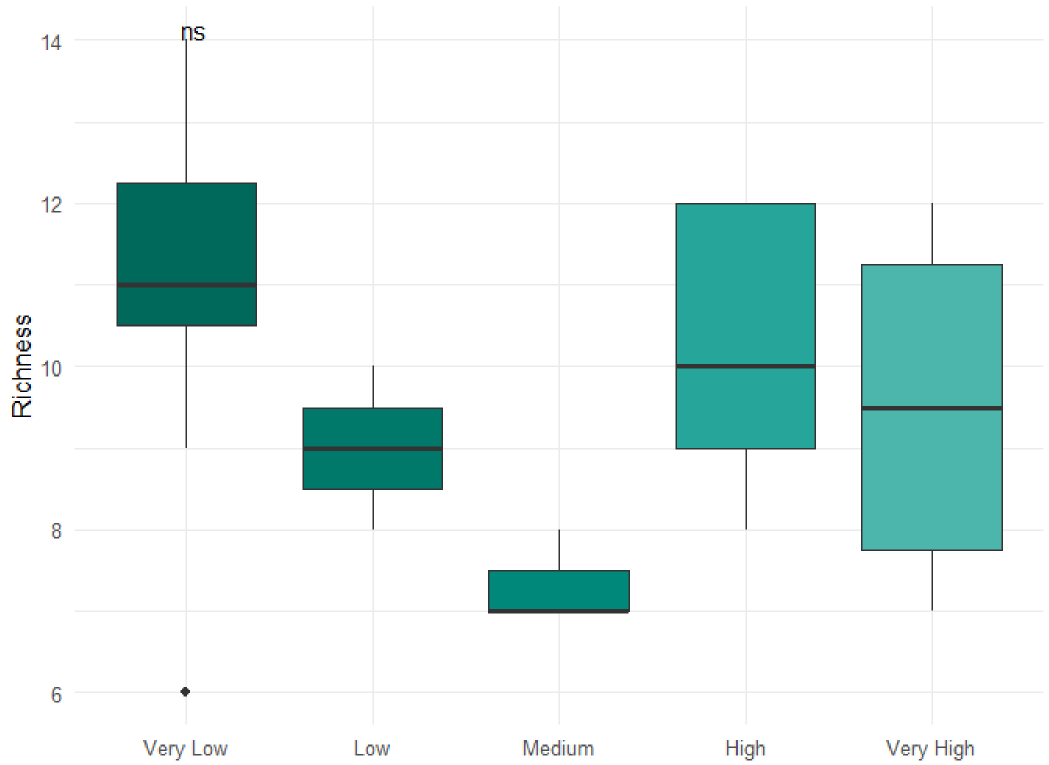

Figure 20. Bird species richness distribution across five classes of TreMs' diversity

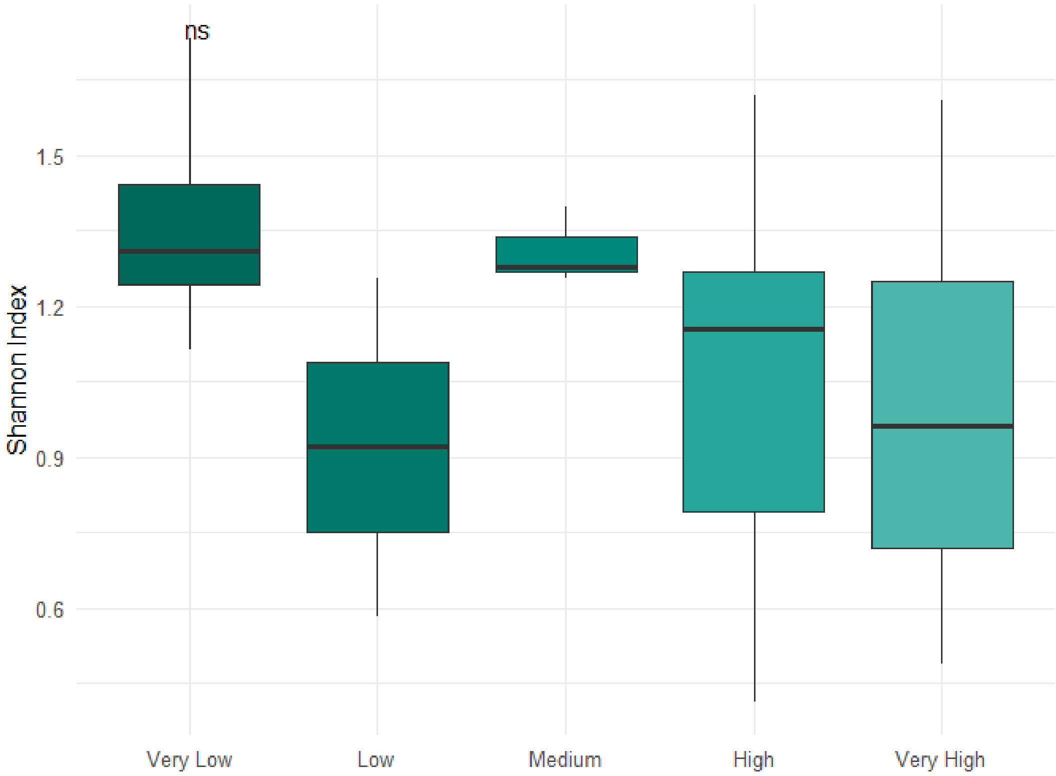

Figure 21. Bird Shannon species diversity distribution across five classes of TreMs' diversity

3.6 Results for bats

The same limitations described for birds apply to bats, as they were sampled in only 24 points across the 12 sites. Therefore, also for this taxonomic group, we tried to identify trends and significant differences in the distribution of species diversity values (species richness and Shannon index) across different classes of IBP and TreM related variables.

Please note that we also subsetted the bats records for narrow space species and attempted the study of the relationships with overall IBP and TreM parameters as well as with specific TreM groups. However, none of these relationships was found to be meaningful.

3.6.1 IBP

Similarly to birds, bats showed a moderate, yet non-significant, increase in species richness from very low to very high value of IBP. Although not significant, this trend is encouraging for the use of the index as a general indicator of biodiversity (Fig. 22).

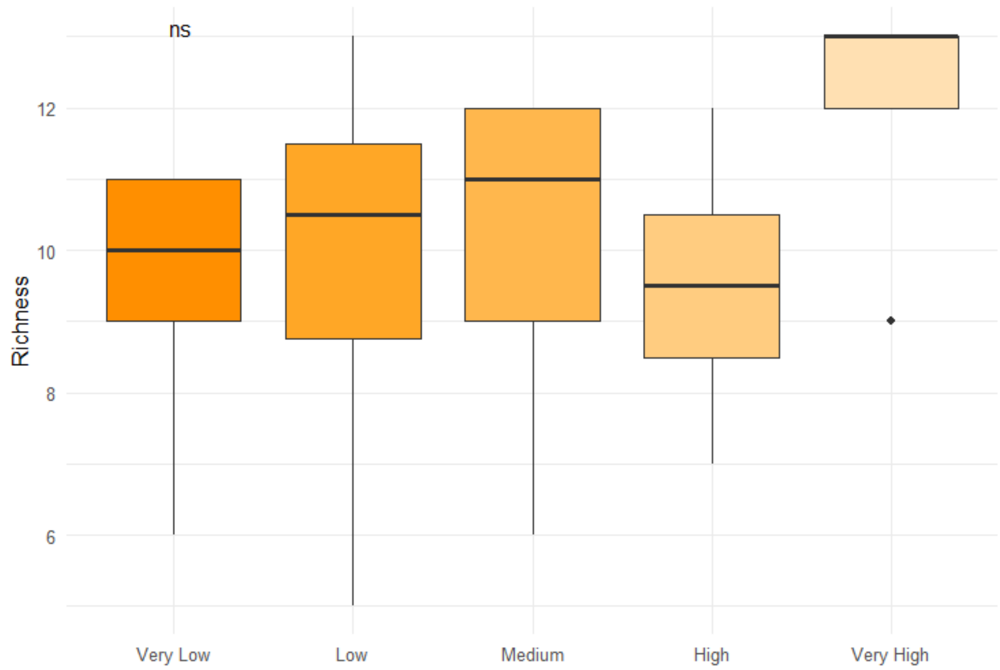

Figure 22. Bat acoustic groups richness distribution across five classes of IBP

Also in this case, such a trend is not confirmed for Shannon index, meaning that the slight trend we identified is driven by non-abundant species (Fig. 23).

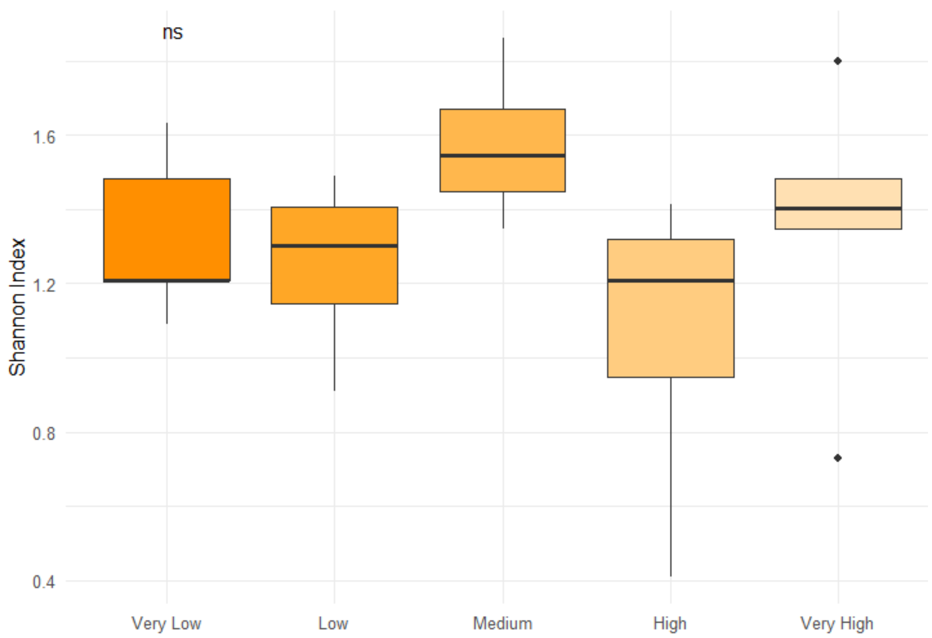

Figure 23. Bat Shannon acoustic groups diversity distribution across five classes of IBP

3.6.2 Abundance and diversity of TreMs

Also bat diversity does not show trends related to TreMs' abundance (Fig. 24-25) or diversity (Fig. 26-27).

Differently from birds, however, most of the acoustic groups' records in the project sites are of groups linked to open or edge conditions rather than to narrow spaces. Therefore, this may be at the base of the scarce relationships of the recorded guilds with TreMs. Also in this case, as for birds, the tree injuries that are often reported as potential shelters for forest bats species (Bütler et al., 2020) occur in almost all sites, as it is for the occurrence of narrow spaces acoustic groups. This type of generalised presence does not allow to highlight any links in terms of species diversity but may give some hints in terms of individual species abundances. It has to be mentioned that temptative models of narrow spaces bat activity against TreMs variable, either generalizing all TreMs or specifically referring to cavities and injuries did not result in significant results.

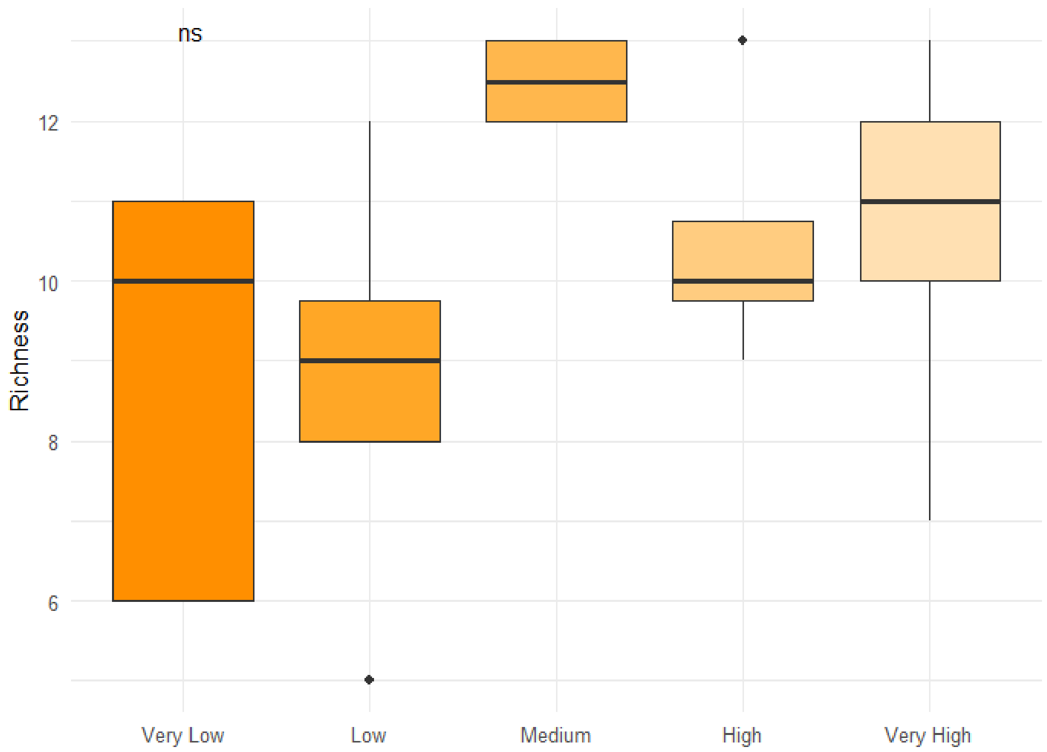

Figure 24. Bat acoustic groups richness distribution across five classes of TreMs' abundance

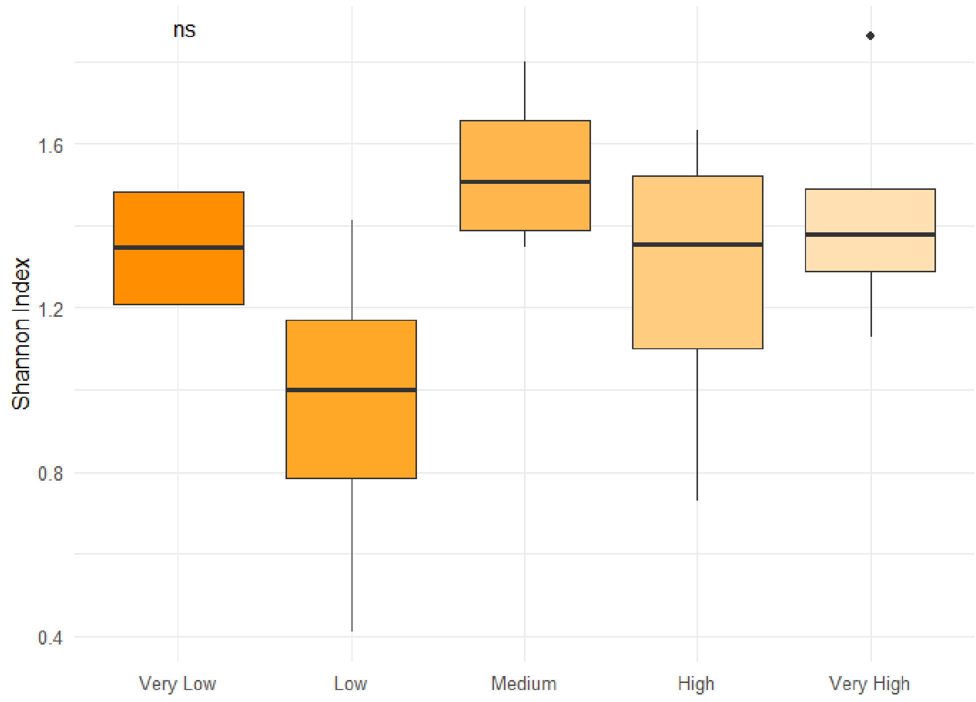

Figure 25. Bat Shannon acoustic groups diversity distribution across five classes of TreMs' abundance.

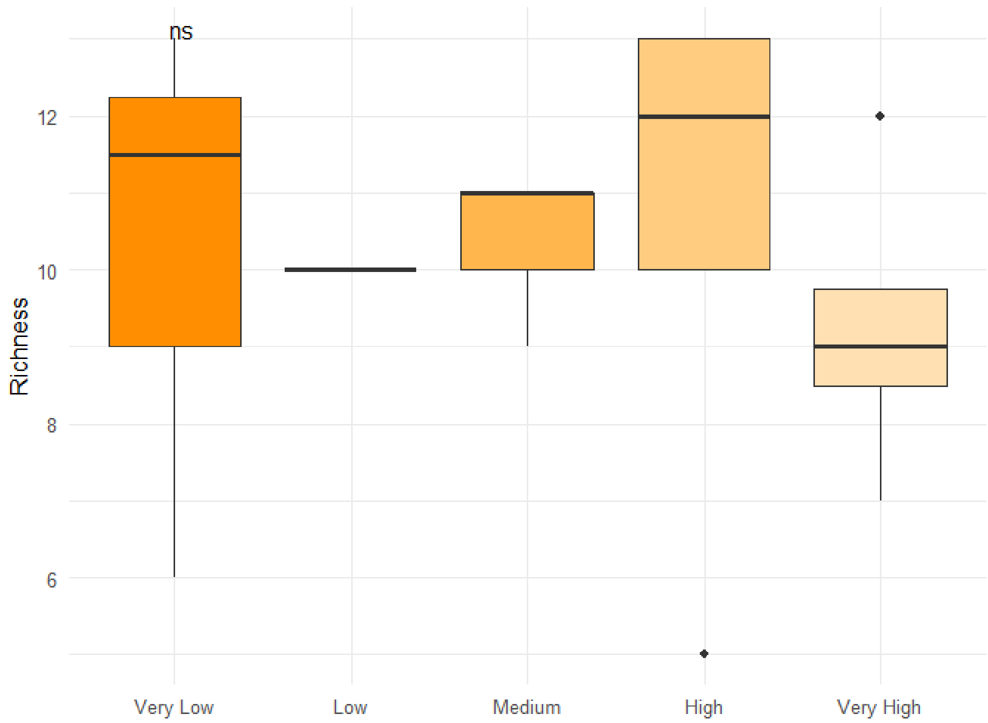

Figure 26. Bat acoustic groups richness distribution across five classes of TreMs' diversity.

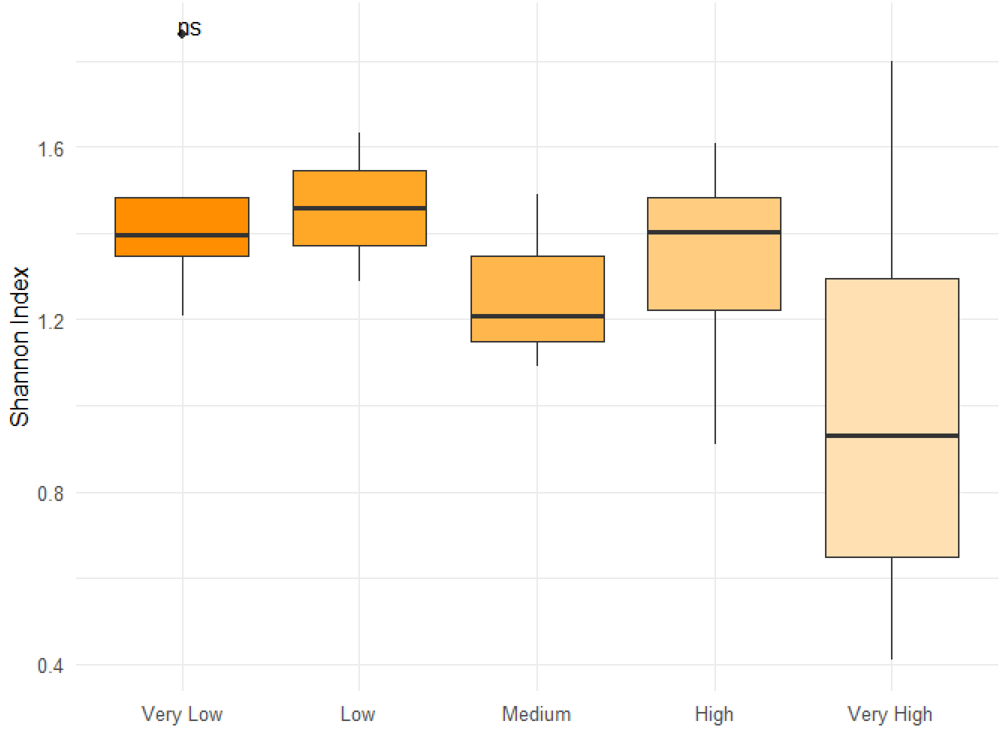

Figure 27. Bat Shannon acoustic groups diversity distribution across five classes of TreMs' diversity.

4. Discussion

The work presented here is of primary relevance since it is the first comprehensive study modeling the diversity of multiple taxonomic groups against a series of structural variables relevant for management purposes and indicators of forest biodiversity within the Mediterranean context across four different countries and habitats. As such, the results here presented are novel and may significantly improve the management and monitoring of the habitats targeted by the project.

Below we summarise the insights for the target habitats' monitoring and management. Interestingly, these two sets of results are tightly intertwined, since the indicators that better describe the habitats' multi-taxon biodiversity correspond to those structural parameters that

4.1. Monitoring implications

4.1.1 IBP indicates the multi-taxon biodiversity of the habitats but should weigh more the openness factor

Overall, the IBP was positively correlated with the diversity values we used for different taxonomic groups. This was true for both saproxylic and phytophagous insects (see SM7), for bats adapted to narrow spaces, and, more weakly, for epiphytic lichens (see SM5). This effect on some specific taxonomic groups, with stronger links to arthropods is in line with a previous study linking IBP to field-sampled biodiversity in temperate forests (Zeller et al., 2022). However, it is important to underline how our results, especially for saproxylic arthropods, which are those showing the strongest response to IBP, show an inflection point that our interpretation associated with low openness values in forest stands with an average IBP value.

This insight is in line with our results for canopy cover (see § 4.2.1) and would support a revision of the scores for the openness factor of the IBP for Mediterranean forest habitats.

4.1.2 The abundance of some TreMs is more relevant than TreMs' diversification

When linking TreM related variables to the diversity of multiple taxonomic groups, we found the abundance of TreMs to be more relevant than their typological diversification. This is true for the habitat diagnostic vascular plant species and epiphytic lichens with similar thresholds indicated by the two models, and for saproxylic arthropods, although with a much greater threshold.

The general significance of the value of this indicator as compared to the number of TreMs type occurring within each sampling unit points to a general effect of the overall structure allowing for a high number of TreMs, rather than to a specific effect of individual TreMs for a set of species or functional groups. As a matter of fact, if individual links between specific groups of saproxylic arthropods and individual TreMs' types were particularly influential, TreM diversification would have emerged as particularly significant. Our results point to the relevance of some TreMs' groups that arose to high abundance in numbers even in plots with a very low diversity. As a matter of fact, only for some of them a direct link with the diversity of the investigated taxonomic groups may be assumed, as it is for the epiphytic and epixylic structures, which directly include the abundance of epiphyte including lichens, and for insect galleries and bore holes, which are directly deriving by the population size of saproxylic communities.

Overall, however, the links between the abundance of the mentioned TreMs and the multi-taxon biodiversity suggests that a relatively high density of large habitat trees, bearing crown deadwood, injuries and excrescences is a general indicator of the habitat conservation status.

Noteworthy, epiphytic and epixylic structures more than other groups of TreMs also indicate a relatively long ecological continuity. This driver of forest biodiversity is inevitably linked to forest structural heterogeneity as well as with the abundance of habitat structures in forests (Nordén et al., 2014). However, it should not be overlooked how allowing for continuous forest cover conditions has a crucial role in the colonisation and long-term maintenance of several forest specialised taxa, as it was demonstrated in temperate oak forests (Mölder et al., 2019) and in Mediterranean forests, in a study including the *Quercus ilex* forests of Luberon (Abadie et al., 2021).

4.2. Management implications

4.2.1 The canopy cover strongly drives the diversity of multiple taxonomic groups

One of the variables that we found more relevant across different taxonomic groups is the canopy cover. This is unsurprising, since the intensity of the light passing through the canopy determines the quantity of energy input for the understorey communities, as well as the microclimate to which they are subjected (De Frenne et al., 2021).

Based on our results the target canopy cover for the target habitats should be higher than 50% to allow for a relatively high abundance of diagnostic species in the understorey, but below 70% because this is a relevant negative threshold for epiphytic lichens. This means that the studied habitats benefit from relatively open conditions as compared to other forest habitats and that the indicators based on tree density used for other forest habitats (Pescador et al., 2019) are unsuitable for these habitats.

The target habitats, like many others within the Mediterranean biogeographical region, have long been subjected to human exploitation, for both timber and fodder. As such, often in space and time, these forests were characterised by a relatively low biomass level, as compared to other European forest habitats, e.g. within the continental biogeographical region. Such a low biomass level is also in line with the relatively low productivity of these ecosystems, which are periodically subjected to a high level of stress linked to the summer drought.

This relatively low canopy cover is also beneficial to arthropods, as indicated by the inflection of the positive link with IBP in the *Quercus ilex* forests with very low openness scores for saproxylic species, and by the negative links between basal area in average diameter classes and phytophagous species. Based on the results for the latter group, it is also evident how the degree of openness in the canopy would be beneficially occupied by shrub species, which may support a functionally diverse community of phytophagous arthropods, and would likely make possible the occurrence of the many shrub diagnostic species of the habitats (see the report D.2.2 *Vegetation-based manual for the recognition and conservation state assessment of the target habitats* for task 2.5).

Also the bat species recorded support the hypothesis that a relatively open canopy could effectively support the bat communities occurring in the project sites. As a matter of fact, 78% of the recorded acoustic groups may be referred to open or edge conditions as defined in Denzinger and Schnitzler (2013).

Therefore, our results give a clear indication on the range of canopy cover (50-70%) to be addressed when managing for a favourable conservation status of the habitat and also indicate as advantageous to favour a shrub cover of at least 20%, especially referred to the habitats' diagnostic species.

4.2.2 TreMs related to senescent trees and ecological continuity are key for the diversity of multiple taxonomic groups

The TreM categories that often were highly abundant also in plots where very few TreMs' types were found were included in the groups epiphytic and epixylic structures, crown deadwood, excrescences, tree injuries and exposed wood, and, among cavities, insect galleries and bore holes.

These TreMs may be promoted within forest ecosystems by releasing the trees either in the larger size classes or showing some senescence signs (Paillet et al., 2017; Spînu, et al., 2022). Another approach would include the active restoration of these structures. This was already attempted within the continental biogeographical region with positive outcomes in terms of TreMs abundance (Asbeck et al., 2023), but no examples are available to the best of our knowledge for the forests within the Mediterranean region.

Given the overall results of the models, our interpretation of biodiversity positive responses was focused on the general forest structure and ecological continuity rather than on specific species-TreM links. In this view, an intermediate approach based on individual tree selection with the release of large and potential habitat trees, with special attention to the forest ecological continuity will allow for a biodiversity increase in the target habitats in the mid- to long-term depending on the original habitat conditions.

4.2.3 The occurrence of deadwood in higher decay classes is crucial for saproxylic arthropods

As highlighted in a global meta-analysis (Parajuli & Markwith, 2023) and only partly confirmed in a European meta-analysis, deadwood decay stage is relevant for saproxylic organisms diversity.

This general positive trend for biodiversity as the decay process advances may be explained by the occurrence in deadwood referred to high decay classes of organisms that are specific to this stage. For beetles, it was demonstrated that the abundance of rare species increases in late successional stages (Clay, 2023), supporting also the diversification in terms of functional groups that we observed.

Since deadwood diameter instead resulted in a neglectable response, in management terms, we would suggest the release of deadwood also in the lower diameter classes in order to facilitate a more rapid decay process towards the advanced stages.

4.3 Opportunities and limitations

The current work represents an unprecedented effort to study the biodiversity of Mediterranean forests, while also investigating its link with management related stand structural variables and structure-based indices of biodiversity potential. The lack of data for Mediterranean forests, with special reference to biodiversity and biodiversity indicators, was already highlighted in previous studies (Burrascano et al., 2023; Larrieu et al., 2018b).

Given the high relevance for European forest diversity of Mediterranean forests and the massive threats posed to these ecosystems by climate changes these data and results are of primary relevance for the conservation of European biodiversity as a whole.

As expected, the novelty of this effort comes together with a series of limitations. The main one is the relatively low number of sampling units as compared to the great heterogeneity found across sites and habitats. Relying on a greater set of data for each individual habitat could have led to more specific outcomes for both the monitoring and the management implications. On the other hand, the target habitats have relevant commonalities in terms of human exploitation, and of relatively low productivity given the drought stress that affects these habitats. These commonalities allowed us to draw general, yet meaningful, conclusions, accounting for the differences across sites and habitats in the BRT models. The sample size limitation was definitely impactful for our conclusions on bats and birds, for which no sound model could have been validated, and further data are certainly needed.

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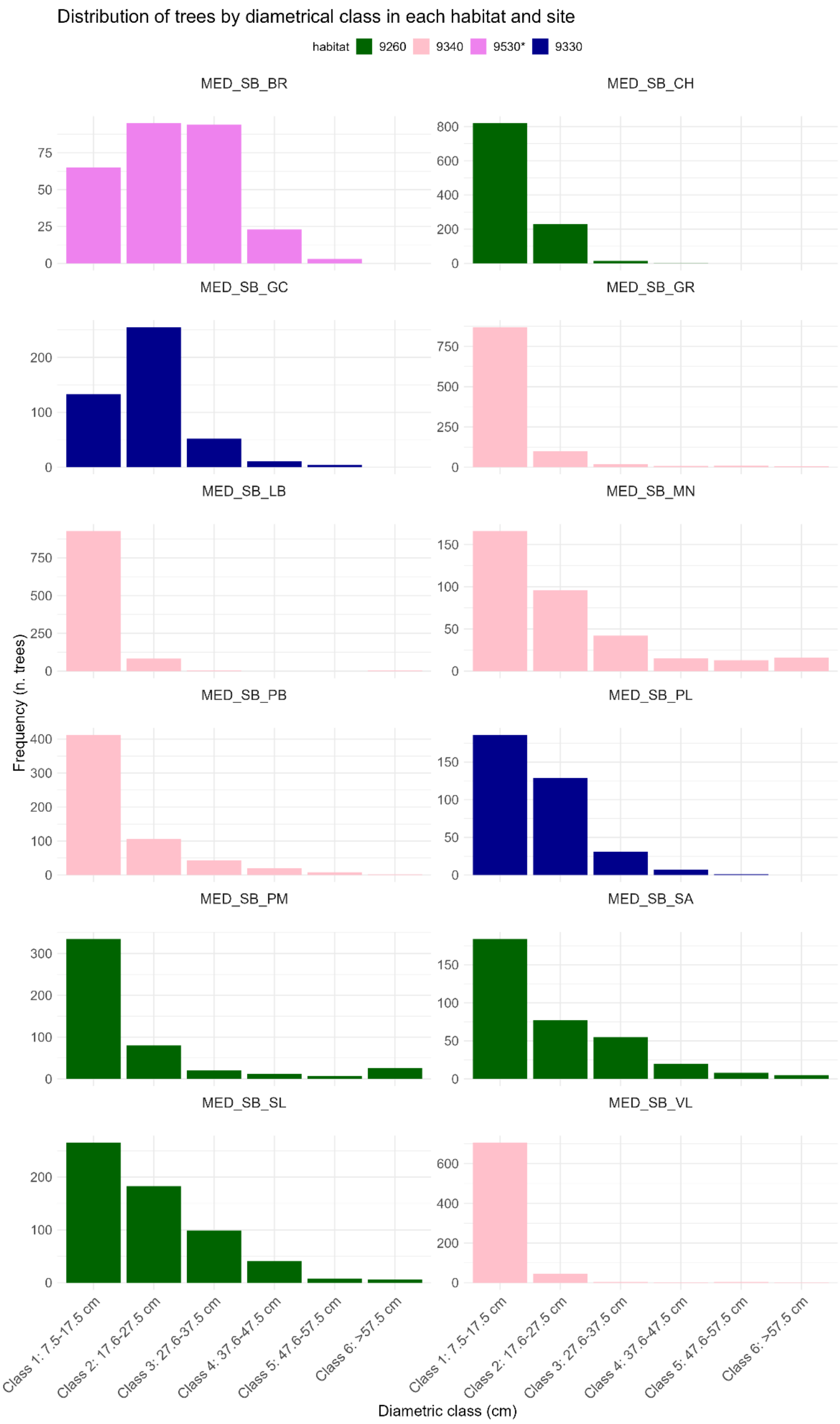
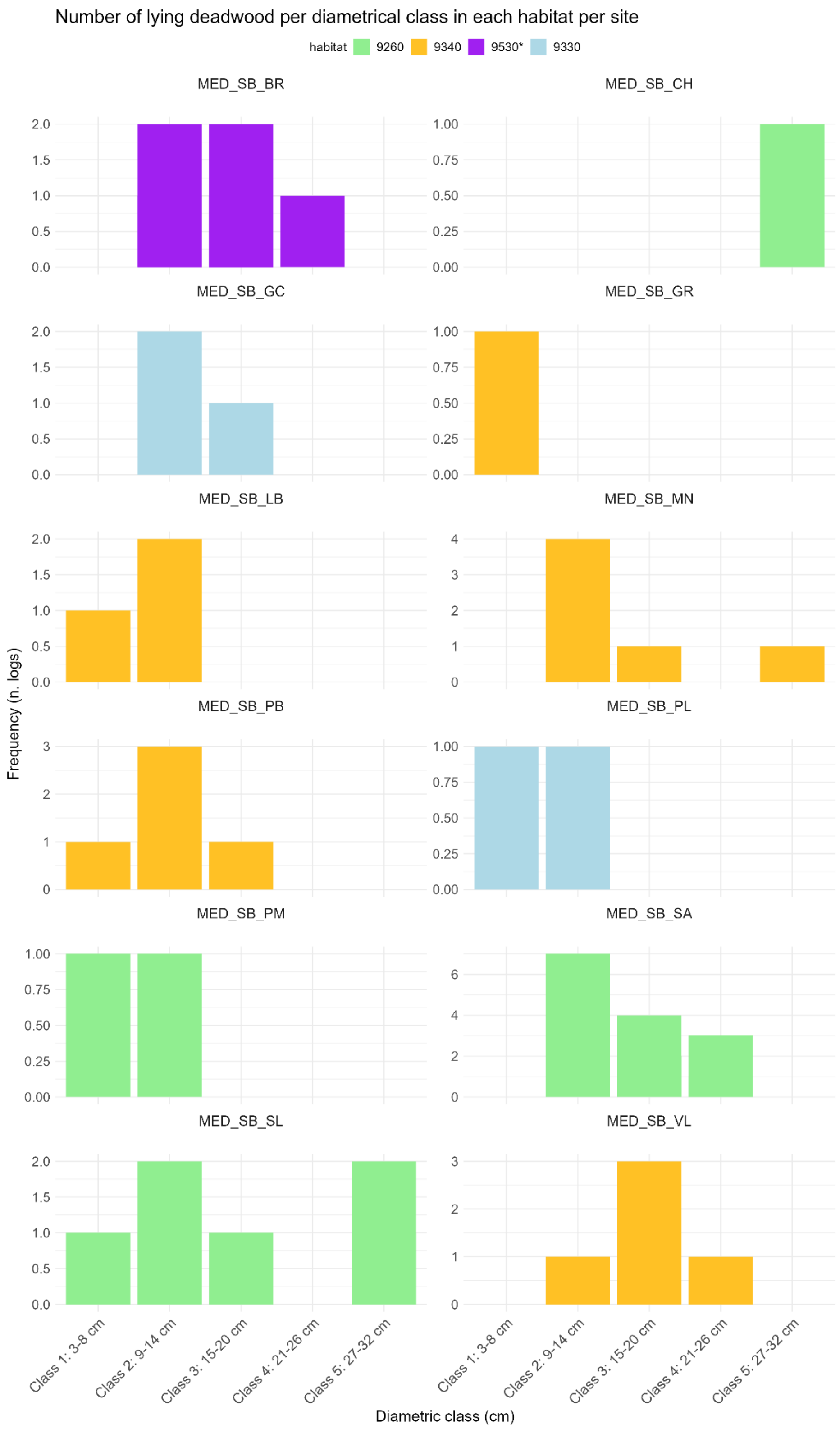
Supplementary material

SM1. Tree diameter distribution across the project sites

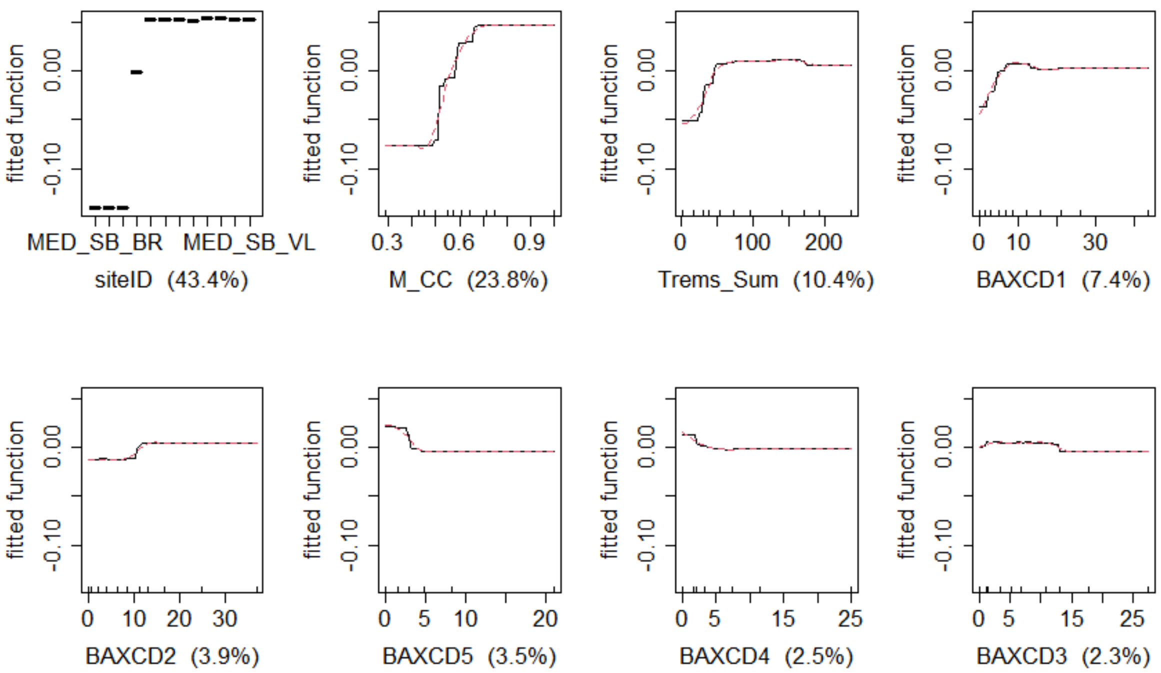


SM2. Lying deadwood diameter distribution across the project sites

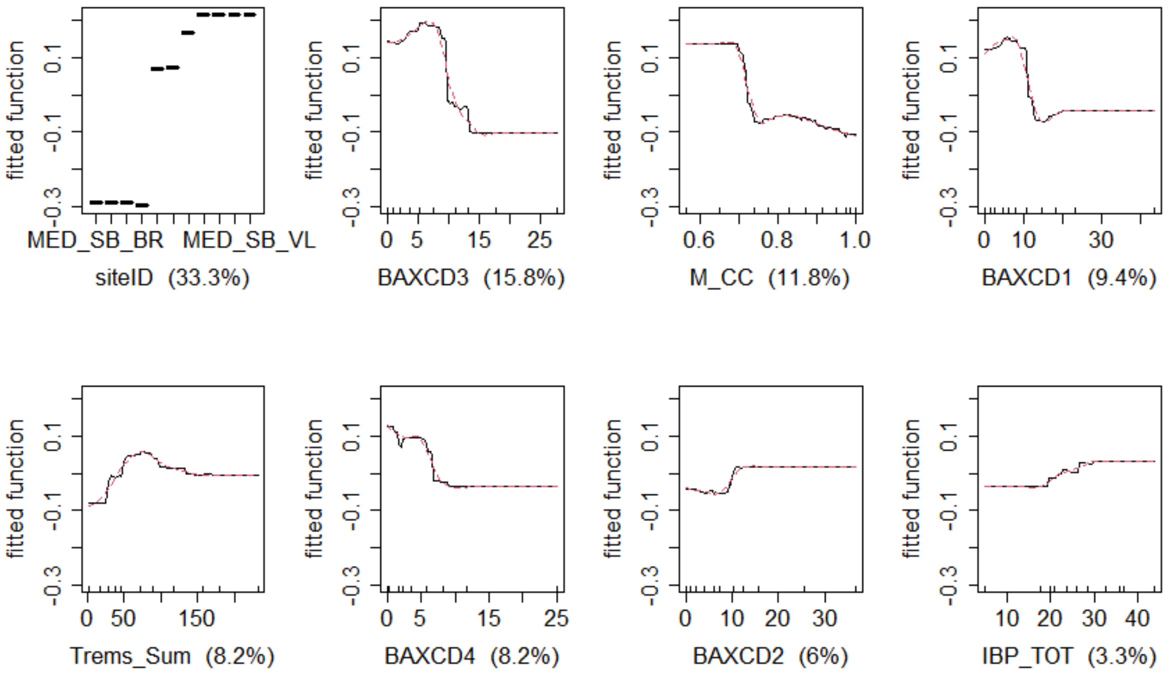


SM3. Distribution across decay classes of the lying deadwood sampled in the project sites

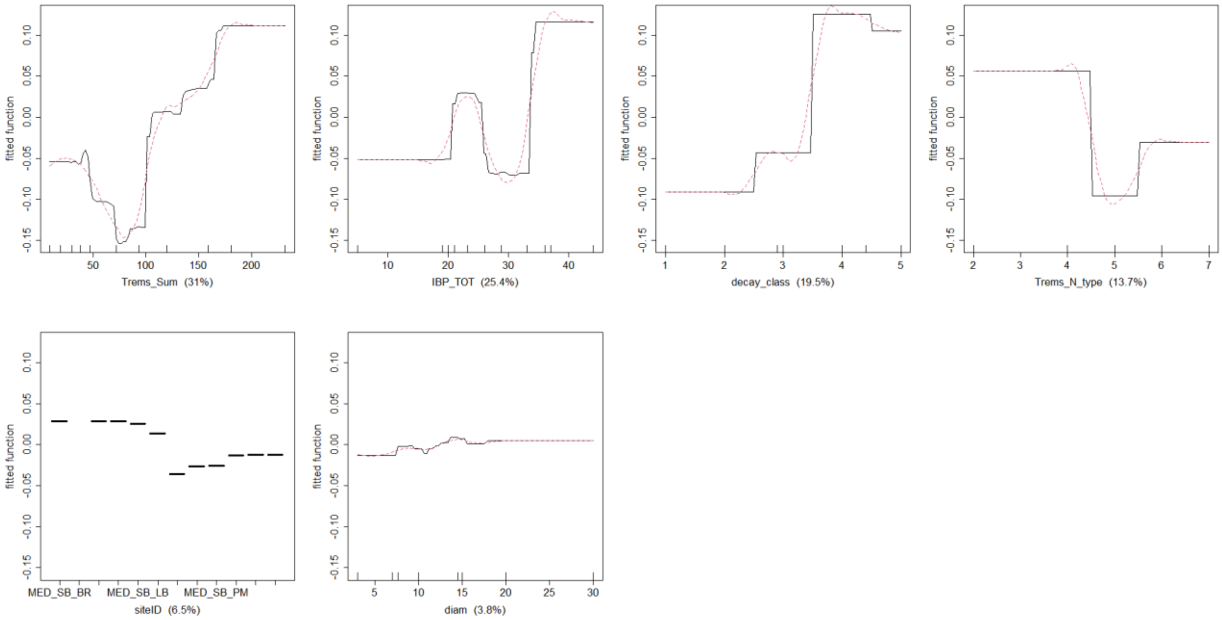
SM4. Partial dependency plots for all variables used in the vascular plants' BRT models



SM5. Partial dependency plots for all variables used in the epiphytic lichens' BRT models



SM6. Partial dependency plots for all variables used in the saproxylic arthropods' BRT models



SM7. Partial dependency plots for all variables used in the phytophagous arthropods' BRT models