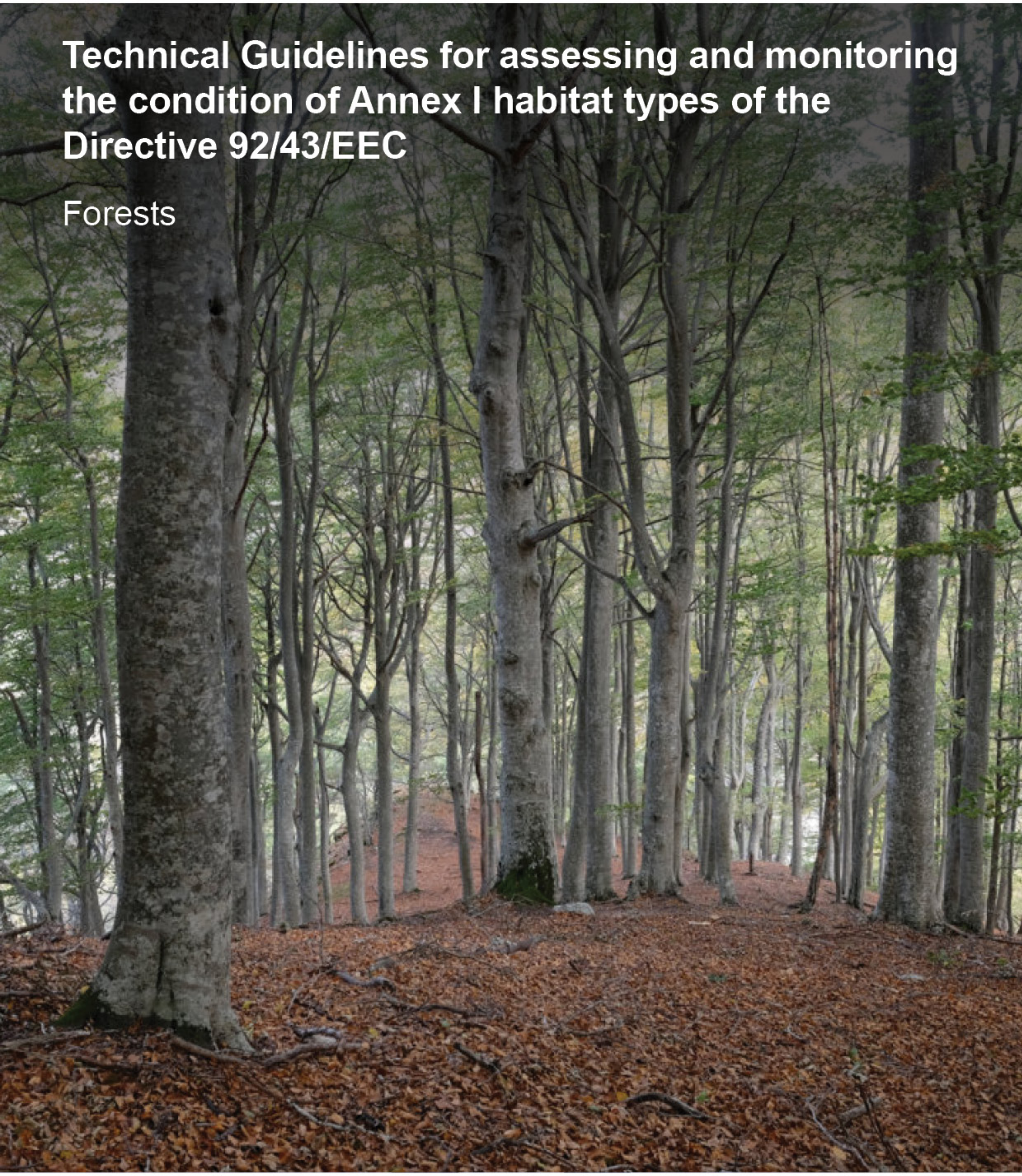
European Commission

Technical Guidelines for assessing and monitoring the condition of Annex I habitat types of the Directive 92/43/EEC

Forests



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Technical guidelines for assessing and monitoring the condition of Annex I habitat types of the Directive 92/43/EC

Forests

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Contents

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Glossary and definitions

Habitats

Natural habitats: are terrestrial or aquatic areas distinguished by geographic, abiotic and biotic features, whether entirely natural or semi-natural (Habitats Directive).

Habitat condition: is the quality of a natural or semi natural habitat in terms of its abiotic and biotic characteristics. Condition is assessed with respect to the habitat composition, structure and function. In the framework of conservation status assessment, condition corresponds to the parameter "structure and function". The condition of a habitat asset is interpreted as the ensemble of multiple relevant characteristics, which are measured by sets of variables and indicators that in turn are used to compile the assessments.

Habitat characteristics: are the attributes of the habitat and its major abiotic and biotic components, including structure, processes, and functionality. They can be classified as abiotic (physical, chemical), biotic (compositional structural, functional) and landscape characteristics (based on the Ecosystems Condition Typology defined in the SEEA-EA; United Nations et al., 2021).

Species

Characteristic species: are species that characterise the habitat type, are used to define the habitat, and can include dominant and accompanying species.

Typical species: are species that indicate good condition of the habitat type concerned. Their conservation status is evaluated under the structure and function parameter. Usually, typical species are selected as indicators of good condition and provide complementary information to that provided by other variables that are used to measure compositional, structural and functional characteristics.

Variables

Condition variables: are quantitative metrics describing individual characteristics of a habitat asset. They are related to key characteristics of the habitat that can be measured, must have clear and unambiguous definition, measurement instructions and well-defined measurement units that indicate the quantity or quality they measure. In these guidelines, the following types of condition variables are included:

- **Essential variables:** describe essential characteristics of the habitat that reflect the habitat quality or condition. These variables are selected on the basis of their relevance, validity and reliability and should be assessed in all MSs following equivalent measurement procedures.
- **Recommended variables:** are optional, additional condition variables that may be measured when relevant and possible to gain further insight into the habitat condition, e.g. according to contextual factors; these are complementary to the essential variables, can improve the assessment and help understand or interpret the overall results.
- **Specific variables:** are condition variables that should be measured in some specific habitat types or habitat sub-groups; can thus be considered essential for those habitats, which need to be specified (e.g. salinity for saline grasslands, groundwater level for bog woodlands, etc.).

Descriptive or contextual variables: define environmental characteristics (e.g. climate, topography, lithology) that relate to the ecological requirements of the habitat, are useful to characterise the habitat in a specific location, for defining the relevant thresholds for the condition variables and for interpreting the results of the assessment. These variables, however, are not included in the aggregation of the measured variables to determine the condition of the habitat.

Reference levels and thresholds: are defined for the values of the variables (or ranges) that determine whether the habitat is in good condition or not. They are set considering the distance from the reference condition (good). The value of the reference level is used to re-scale a variable to derive an individual condition indicator.

Condition indicators: are rescaled versions of condition variables. Usually, they are rescaled between a lower level that corresponds to high habitat degradation and an upper level that corresponds to the state of a reference habitat in good condition.

Aggregation: is defined in this document as a rule to integrate and summarise the information obtained from the measured variables at different spatial scales, primarily at the local scale (sampling plot, monitoring station or site).

Abbreviations

ECT: Ecosystem Condition Typology

EU**:** European Union

MS: Member State

EU Member States acronyms:

Austria	(AT)	Estonia	(EE)	Italy	(IT)	Portugal	(PT)
Belgium	(BE)	Finland	(FI)	Latvia	(LV)	Romania	(RO)
Bulgaria	(BG)	France	(FR)	Lithuania	(LT)	Slovakia	(SK)
Croatia	(HR)	Germany	(DE)	Luxembourg	(LU)	Slovenia	(SI)
Cyprus	(CY)	Greece	(EL)	Malta	(MT)	Spain	(ES)
Czechia	(CZ)	Hungary	(HU)	Netherlands	(NL)	Sweden	(SE)
Denmark	(DK)	Ireland	(IE)	Poland	(PL)		

NFI: National Forest Inventory

SEEA EA – System of Environmental Economic Accounting- Ecosystem Accounting

Executive summary

The Forests habitats covered in these guidelines encompass natural and subnatural woodland vegetation, e.g., forests of native tree species, also enclosing old, naturalised plantations of native tree species, riparian habitats, bog woodlands and wooded dunes. The Directive classifies forest habitats within Group 9 and most of these habitats corresponds to Boreal, Temperate, mountainous and Mediterranean European forests. Their ecological characterization is given by their climatic requirements, with a positive water balance and not too cold temperatures, well-structured soils and sufficient time to develop. Their species exhibit different functional strategies, determined by attributes related to phenology, ecophysiology, life history and demography. These habitats exhibit a series of successional stages that are interrupted by disturbances, thus determining disturbance regimes consubstantial to them. European forests have experienced profound historical transformation due to human activity, and primeval, historically unmanaged forests are the exception. Many forested areas persist, often fragmented, subjected to forestry management leading to important modifications in their structure and composition. Particularly, recent farming abandonment is driving the growth of new forests which, in some regions have not attained mature successional stages.

The analysis of existing methodologies across EU Member States reveals significant variability in assessing and monitoring these habitats. However, compositional characteristics, particularly characteristics and typical species, are widely used to assess habitat condition. Structural variables, including large/old trees, deadwood, and vertical layers cover also common. Functioning-related variables, such as soil characteristics, biotic interactions, remain underrepresented in most methodologies, maintaining a static vision that limits the ability to comprehensively assess ecosystem processes and services. Landscape-level variables, are poorly considered, and are mostly referred to fragmentation metrics. Although these variables are similar in their foundation, thresholds for interpreting these metrics and procedures are often based on exert judgement, which often is poorly justified or absent. Similarly, aggregation procedures exhibit notable differences among MSs, particularly at stand or local level, though procedures for aggregating variables at the supra-local level tend to converge. Monitoring procedures are largely based on periodic field observations, with a relevant role of National Forest Inventories.

A set of essential, recommended and specific variables for monitoring Forest habitat are proposed. They are categorized into abiotic (e.g., bare soil, litter depth, soil organic matter, acidity), biotic (e.g., characteristic and typical species, tree richness and alien species), structural (e.g., canopy cover, layer stratification, large living trees and woody debris), functional (e.g., canopy health, human-induced impact, non-human disturbance, regeneration), and landscape (e.g., patch size, fragmentation). Although remote sensing technologies should be further incorporated in forest habitat assessments, they require field data for training, calibration, and validation to model reliable relationships between forest canopy metrics and biodiversity and habitat functionality. The main criteria and guide for reference values and critical thresholds determining favourable condition are provided, but specific values should consider their specifics, regarding the considered variable, the particular habitat, the contextual biogeographical gradients, and the historical, cultural and socio-economic background. An aggregation procedure based on hierarchically combining minimum aggregation rules for essential variables and quantitative methods to all variables is also proposed.

The guidelines outline several priority areas for future efforts, including maintaining the exchange of information between MSs, moving to the definition of common methods, for instance, by training and evaluation programmes, exploring new data sources (e.g., climatic ones), incorporating remote sensing methodologies, and integrating climate change impacts into monitoring. Strengthening knowledge exchange, technology sharing, and coordinated efforts is critical to fostering an inclusive, collective approach to conservation. Aligning methodologies with EU biodiversity policies, particularly the Nature Restoration Regulation, will be vital in achieving restoration and conservation goals.

1. Definition and ecological characterisation

1.1 Definition and interpretation of habitats covered

This document covers all forest habitats included in Forest Group 9 of the Habitats Directive (except for 9070 - Fennoscandian wooded pastures, which is included in the guidelines for grassland habitats). All these habitats have similar ecological characteristics and monitoring requirements. In this forest group, however, riparian habitats and bog woodlands have particular characteristics and requirements that merit consideration. This document will therefore include only some particular details about these habitats. Wooded dunes will also be considered and details for monitoring them are covered separately in the guidelines.

Group 9 comprises natural and sub-natural woodland vegetation, e.g., forests of native tree species with a high degree of naturalness and/or which have benefited from continuous sustainable management over a significant period. Consequently, old, naturalised plantations of native tree species (e.g., *Pinus* spp., *Castanea* spp.) are also included.

The diversity of European forest habitats depends on climate and on specific site conditions (e.g., edaphic and hydrological). In addition, human activities have a strong influence on the diversity and naturalness of European forests. Forest habitats in Annex I of the Habitats Directive are divided into six subgroups, mainly according to biogeographical regions.

- **Forest habitats of boreal Europe** (subgroup 90)

This group corresponds to subgroup 90 in the Habitats Directive. It includes forests in the European boreal zone (also known as the taiga zone) and hemiboreal zone, and some forests in the Nordic alpine zone (habitat type 9040). Late-successional stages include coniferous and mixed broadleaved-coniferous forests, which are dominated by two conifer species − Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). Birch species (*B. pubescens, B. pendula*) and other deciduous trees such as aspen (*Populus tremula*), rowan (*Sorbus aucuparia*) and grey alder (*Alnus incana*) are frequently found growing amongst the conifers and are particularly characteristic of early-successional stages.

Hemiboreal forests are found in the transition zone between the boreal and temperate zones. As a result, they are characterised by the coexistence of boreal coniferous and temperate broadleaved tree species (*Fraxinus excelsior, Ulmus glabra, Tilia cordata, Quercus robur*). While a large number of herbs tend to dominate the hemiboreal forests, moving further north, in the boreal zone, they become scarcer − being restricted to nutrient-rich sites and early-successional stages – and are replaced by ericaceous dwarf-shrubs. In the middle and northern boreal zones, ericaceous plants, bryophytes and lichens tend to be the dominant components of the understory.

- **Forest habitats of temperate Europe** (subgroups (91 and 94)

The forests of temperate Europe are divided into two subgroups (91 and 94). Subgroup 91 comprises mainly **temperate broadleaved deciduous forests** mostly found in the Atlantic, Continental and Pannonian biogeographical regions. When abiotic conditions are favourable, in nutrient rich soils, temperate forests are formed by a mixture of many species (*Carpinus betulus, Quercus petraea, Q. robur, Fraxinus excelsior, Acer platanoides, A. pseudoplatanus, Tilia cordata, T. platyphyllos,* and *Fagus sylvatica*). Oak and beech species tend to dominate temperate forests when local biotic conditions become harsher and soils more acidic (see 1.2 Environmental and Ecological Characterisation). Conifers are rarely found in these forests. *Taxus baccata*, *Pinus sylvestris* and *Abies alba* may form **mixed broadleaved-coniferous**

forests or even be locally dominant in ecotones, specific substrates or mountainous areas (for example Habitat Types 91P0, 91Q0 and 91T0).

Subgroup 94 comprises **temperate mountainous coniferous forests** found in the alpine biogeographical region. Climatic conditions are similar to those of the boreal zone, except for the light regime and length of the day. Being boreal forests, they are dominated by coniferous trees. In addition to boreal conifers (*Picea abies, Pinus sylvestris*), other species such as *Abies alba, Pinus mugo, Larix decidua, Pinus cembra* and *Pinus nigra* occupy high altitudinal belts of central European mountains, rocks of Balkan peninsula and the Scandinavian Alps.

- **Forest habitats of Mediterranean Europe**

Mediterranean forests are divided into three subgroups**: Mediterranean deciduous** (subgroup 92); **Mediterranean sclerophyllous** (subgroup 93) **and Mediterranean and Macaronesian mountainous coniferous** (subgroup 95). Mediterranean deciduous forests are deciduous and semi-deciduous forests found in wetter and colder areas of the Mediterranean biogeographical region which may be considered transition zones with the Atlantic biogeographical region (Sub-Mediterranean). These forests are formed by a mixture of Quercus (*Q. pubescens, Q. pyrenaica, Q. faginea, Q. cerris, Q. frainetto, Q. trojana*), Acer (*Acer monspessulanus, A. opalus, A. obtusatum*), *Ostrya carpinifolia, Fraxinus ornus, Carpinus orientalis*, etc. Old, established and naturalised plantations of chestnut (*Castanea sativa*) are included in this group.

Mediterranean sclerophyllous forests are mainly constituted by broadleaved evergreen oak species (Quercus species: *Q. suber, Q. ilex, Q. coccifera, Q. alnifolia*), forming woodlands, but also by other broadleaved sclerophyllous species such as olive (*Olea europaea var. sylvestris*) and carob (*Ceratonia siliqua*).

Macaronesian laurel forests and palm groves of Phoenix spp. are usually included in this subgroup. Finally, **Mediterranean and Macaronesian mountainous coniferous forests** are dominated by xerophytic conifer species found in the Mediterranean and Macaronesian biogeographical regions. These include pines (*Pinus nigra, P. pinaster, P. pinea, P. halepensis, P. brutia, P. canariensis*), firs (*Abies pinsapo, A. nebrodensis, A. cephalonica, A. borisii-regis*), junipers (*Juniperus thurifera, J. phoenicea, J. oxycedrus, J. excelsa, J. foetidissima, J. drupacea, J. cedrus, J. brevifolia*), cypress (*Cupressus sempervirens*), cedar (*Cedrus brevifolia*) and *Tetraclinis articulata*.

Other "azonal" forests, i.e., forests that depend mostly on site-specific ecological conditions, such as **mire and swamp forests** and **alluvial and riparian forests**, are included in their correspondent "zonal" subgroup, i.e. their general biogeographical region, e.g., "91D0 Bog woodlands" into subgroup 91 (Temperate forests) and "92A0 *Salix alba* and *Populus alba* galleries" into Mediterranean ones.

Finally, there are a few wooded habitats that have not been included in Forest Group 9: **wooded dunes** (2180 "Wooded dunes of the Atlantic, Continental and Boreal region", 2270 "Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*"), **wooded grasslands** ("6310 Dehesas with evergreen *Quercus* spp." and "6530 Fennoscandian wooded meadows"). Since most of the methodologies used for monitoring forest condition in wooded dunes are similar to those used for forest habitat types, in this guide we have clustered all forest habitats, including wooded dunes (habitats 2180 and 2270). On the other hand, Fennoscandian wooded pastures (habitat 9070) are covered in the Technical Guidelines for natural and seminatural grasslands together with some other wooded grasslands, as "dehesas" (habitat

6310) and Fennoscandian wooded meadows habitat 6530, where their woody component is also considered, as appropriate.

Table 1. Forest habitat types covered in these guidelines

Forest habitat group / type		Number of habitat types
Code	Name	
90	Forests of Boreal Europe	5
91	Forests of Temperate Europe	37
92	Mediterranean deciduous forests	13
93	Mediterranean sclerophyllous forests	8
94	Temperate mountainous coniferous forests	3
95	Mediterranean and Macaronesian mountainous coniferous forests	10
2180	Wooded dunes of the Atlantic, Continental and Boreal region	1
2270	Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*	1

1.2 Environmental and ecological characterization and selection of variables to measure habitat condition

1.2.1 Ecological characterization of forests

Forest ecosystems – i.e., with a tree canopy cover of at least 10 percent and tree height of 5 m or more, according to the FAO (1998) − are characterised by the dominance of trees belonging to a single or to several species (mixed forest). This means that primary production (assimilation of radiative energy) is carried out at a distance from the ground by tall-statured, long-lived woody plant species which have a competitive advantage owing to light interception. This characteristic enables forests to accumulate a great amount of biomass, which requires time to decompose after death, making them important carbon stocks.

Forests, therefore, require (1) a **climate** within certain margins determined by (i) a positive **water** balance (availability of water relative to the evapotranspirative demand induced by environmental temperature) and (ii) **temperatures** that are not cold enough to cause freezing-induced cavitation in the conductive tissues, or to damage buds located at a distance from the ground; (2) well-structured **soils** that allow tree root systems to function properly (aeration, storage and exchange of water and nutrients, support for aerial tree structures); and (3) sufficient **time** for trees to develop their structures.

There are different **functional strategies** (determined by attributes related to phenology, ecophysiology or life history and demography) for meeting such environmental requirements. These strategies are set at the species level, so the taxonomic identity of trees is commonly associated with different combinations of functional traits that represent adaptations to the particular features of forest environments.

Long-lived woody structures modify the physical and chemical forest environment, creating **microclimates and microhabitats** that promote biodiversity, a common characteristic of forests. This biodiversity plays an important role in the functioning of the forest ecosystem, e.g., it contributes to nutrient recycling and tree uptake of nutrients from the soil.

The **temporal dimension** is very important in forests, since the development of their full structural properties requires time. For this reason, the integrity of the forest ecosystem includes a series of stages that occur over time (**succession**) until maturity is reached. When this succession is interrupted by disturbances, or when stages of senescence are reached, the forest system should include elements (e.g., small or **regenerating plants**) that enable succession to resume.

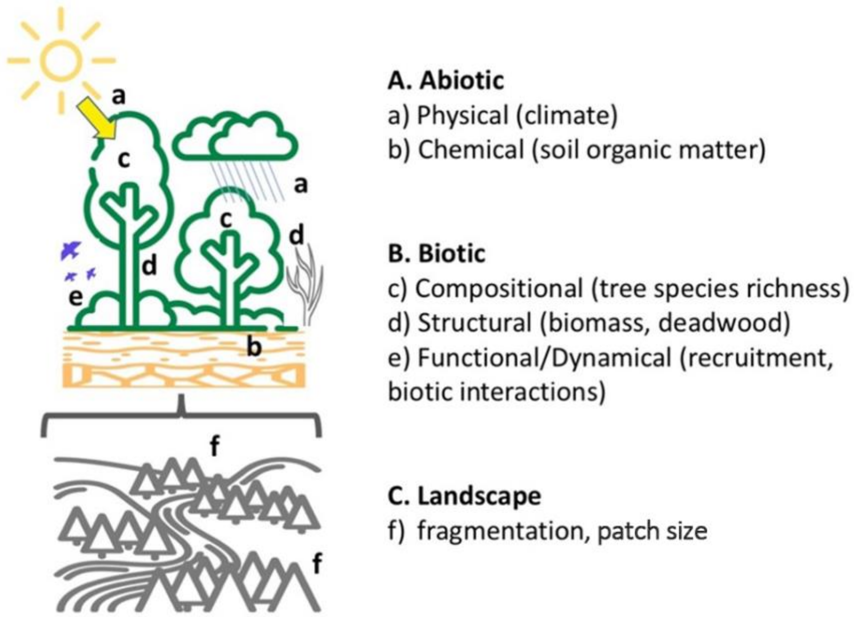
European forests have experienced profound historical transformation due to human activity. There is a consensus that primeval forests are the exception, restricted to a few remote areas, mainly in mountains or marshlands (Sabatini et al., 2018). Many forested areas were cleared centuries ago for agricultural and rangeland use and the remaining forests were commonly restricted to unproductive sites with shallow soils and/or steep slopes. However, forested areas persist, covering large though often fragmented extents that have been subjected to forestry management for the provision of wood-related goods or for soil protection and water cycle regulation. In general, forestry determines important modifications in stand characteristics in terms of structure (promoting even-aged, homogeneous stands) and composition (selecting for more productive species, establishing plantations or favouring the introduction of alien species). Recent farming abandonment is driving the growth of new forests which, are vulnerable to extreme disturbance regimes such as windfalls, wildfires and pest outbreaks which hardly correspond to a natural disturbance regime. On the other hand, forest expansion provides opportunities for contributing to the European restoration policy agenda with regard to climate change mitigation, biodiversity conservation and bioeconomy (Frei et al., 2024).

1.2.2 Main ecological characteristics and identification of variables to measure habitat condition

In this section, the description of key characteristics and the corresponding variables useful for measuring forest condition follows the Ecosystem Condition Typology (ECT) defined in the framework of the System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA EA), adopted by the United Nations Statistical Commission as the international standard for ecosystem accounts (United Nations et. al., 2021), which is also integrated and proposed in the EU-wide methodology for mapping and assessing ecosystem condition (Vallecillo et al., 2022).

According to this framework, ecosystem characteristics refer to the system properties of the ecosystem and its major abiotic and biotic components, while ecosystem condition is the quality of an ecosystem measured in terms of its abiotic and biotic characteristics. In this section we depart from the general characteristics that define the structure and function of forests to identify feasible variables that will eventually allow the assessment of condition according to a set of selection criteria (e.g., relevance, directional meaning, sensitivity to human influence, validity, reliability, availability, simplicity, compatibility, comprehensiveness and parsimony (Czúcz et al., 2021). The SEEA Ecosystem Condition Typology is a hierarchical typology for organising data about ecosystem condition characteristics, and may be available at different spatial scales, from plot-level in-situ monitoring to data at the country or EU level. It can be used as a template for selecting variables and indicators and it provides a structure for aggregation. The ECT also establishes a common language to support increased comparability among different ecosystem condition studies. The ECT has six classes of characteristics: abiotic physical, abiotic chemical, biotic compositional, biotic structural, biotic functional and landscape, as illustrated in Figure 1.

Figure 1. Ecosystem characteristics of forest habitats



Abiotic characteristics

Forest **abiotic ecosystem characteristics** are related to the physical environment which is determined by climate variables (precipitation, light, temperature and wind), topography, soil characteristics, hydrological conditions and air quality. For example, gas exchange within forest canopies depends on the microclimatic condition within the forest, and also on edaphic factors and water availability. The abiotic variables to be measured following the SEEA EA are categorised as physical and chemical.

Physical characteristics

- **Temperature and precipitation**. Forests can occur under a wide range of temperatures encountered in Europe. Low temperatures determine the limit of forest distribution and the prevalence of more freeze-tolerant species such as conifers in boreal high mountain forests. Together with radiation seasonality, they also determine the prevalence of broadleaved deciduous species in temperate and continental regions; whereas evergreen species, including conifers, tend to prevail in Mediterranean-climate areas. In fact, the balance between water demand, largely controlled by temperature, and water availability, climatically controlled by precipitation, determine the functional characteristics of forests (e.g., estimated by ETp-related indices) (Perry, 2008). However, these variables barely determine forest habitat condition, other than overall stress and extreme episodes associated with climate change.
- **Radiation**. Radiation reaching the ground in forests plays an important role in microclimate (temperature, moisture) conditions, which in turn influences key processes such as decomposition, creation of microhabitats for biodiversity, and resources availability. It also determines species composition. With regard to temperature and precipitation, these are not considered for determining habitat condition.
- **Physical soil characteristics**. These include texture, structure, porosity and bulk density. In general, key soil characteristics for good forest condition include the absence of bare or

eroded soils (except in habitats where recurrent disturbances are a natural component), low compaction, and well-structured, deep soils with organic matter and litter layer (Pescador et al., 2022; Maes et al., 2023). Nevertheless, good condition can be attained in naturally established forests on thin soils, such as those on rocky outcrops. Historical continuity of forests is highly important for soil development and humus accumulation in the top soil layers.

- **Water regime**. Characteristics related to the hydrological conditions and flood regime are determinant for certain forest habitats, such as those associated with rivers and bogs. Specific types are forests in riparian areas or bogs, or on sandy soils with low water retention. For example, the presence of water bodies may be important to some components of forest biodiversity, or the modification of the flooding regime by dams and reservoirs may disrupt the functioning and dynamics of water-table-dependent riparian forests (Gonzalez et al., 2012), which may also be sensitive to human-induced changes in groundwater levels, as a result of irrigation, for example. In addition, peatland ditching, which particularly affects bog woodlands, produces relevant hydrological changes in large areas of northern regions.

Chemical characteristics

The main chemical characteristics of forests relate to soil properties. Soils are the result of an intricate integration of physical, chemical and biotic components, which eventually offer basic requirements (water, nutrients, anchorage) to forests for developing.

- **Chemical soil properties** relevant to forest condition include deviations in pH and nutrient content at baseline level. Forests occur on soils across a wide range of pH and, based on soil reaction, depending on the chemistry of the bedrock and leaching. Therefore, soils are broadly recognized as acid, derived from siliceous or plutonic bedrock, or leached soil, and base-rich soil derived from calcareous bedrock. However, pH can decrease due to atmospheric deposition (acidification) or increase due to liming. Nutrient cycling and availability are strongly associated to the decomposition process, which is also linked to acidity. Thus, litter and soil organic matter content constitute key indicators of forest condition. Particularly, soil organic matter is often used as a proxy of soil health and quality (Zornoza et al., 2015) and has therefore been used as an integrative indicator of habitat condition (Maes et al., 2023).

Biotic characteristics

Compositional

These characteristics correspond to the assembly of species that constitute forests. This category comprises several groups of characteristics:

- **Characteristic and typical species**. Forest habitats are often determined by sets of species, according to local abiotic conditions, biogeographical context and species pool (Tichy et al., 2022; Dengler et al., 2023). Within this set of species, **characteristic species** are used for identifying the habitat type, in accordance with the Interpretation Manual of EU Habitats, which provides a formal list of characteristic species for each habitat, while **typical species** include those that are good indicators of favourable habitat quality. Though conceptually distinct, some characteristic species may also be considered typical species. Therefore, local inventories may be contrasted with the set of species that would find this habitat suitable (Bastrup-Birk et al., 2014; Marín et al., 2021). Characteristic species can be considered assemblages of species, with variation among European regions that are within the same habitat type, and they often correspond to phytocenological categories (but see 1.3.). Typical species are those that are sensitive to changes in the condition of the habitat and may belong to any taxonomic group, including lichens, bryophytes, fungi and animals, particularly birds, although most of the species considered are vascular plants. Tree species have a fundamental value in evaluating forest habitat condition (Kovac et al., 2016), although shrubs and herbs may also provide relevant insights. Animal species should also be considered in most forest habitats, while bryophytes, lichens and fungi are particularly relevant in some habitats, such as boreal forests (Kimberley et al., 2013; Brown et al., 2020). See 1.3. for further details about selecting typical species. Given the ecological and geographical variability of forest habitats, different typical species may be identified in different parts of the range of a habitat type.

- **Species richness**. The number of species per unit area is a key characteristic of any habitat. In forests, it is important to determine tree richness – particularly in the canopy−, species richness of other plant growth forms (e.g., shrubs, herbs), and total richness (Alberdi et al., 2016; Marín et al., 2021; Pescador et al., 2022), and also to include lichens, bryophytes, fungi and animals. However, raw values of species richness may include trivial or even harmful species. Therefore, species richness should be accompanied by an assessment of their ecology. For example, the richness of particular types of species sensitive to environmental stress or disturbance, such as endemic species, those of floristic interest, and endangered species (e.g., threatened forest birds, and some beetles), may be of interest as indicators of forest habitat condition (Maes et al., 2023).
- **Alien species**. Alien species, particularly invasive species, affect the naturalness of habitats and constitute an important characteristic to be recorded (Keller et al. 2011; Alberdi et al. 2016). There are reference lists which even may normatively determine some degree of monitoring and/or management (EU 2014). It is important to make the distinction between those which directly achieve forest canopy from those in the understory, including herbaceous aliens. Also, it is important to recognize invasive/expansive performance and harmful impacts, for instance on native species and functional properties.
- **Harmful species**. These are species that have a negative impact on forest habitat condition in terms of composition, structure or functioning, despite being native. This is due to their great colonising ability or growth rate, which enables them to achieve competitive dominance (which is why they are often referred to as expansive species). They often appear after disturbances or nutrient deposition and can be indicators of habitat alteration. Sometimes, when impact is the main criteria of recognition, their distinction from alien species is not specified.

Structural

Structural characteristics describe the pattern of space occupancy, which is determined by the capacity for carbon assimilation and biomass storage, thus creating microhabitats for biodiversity. Structural characteristics associated with old, large trees and standing or decaying deadwood are generally recognised as indicators of forest maturity (Mosseler et al., 2003; Wirth et al., 2009; Burrascano et al., 2013), regardless of the type of forest habitat, and therefore are associated with favourable condition (Alberdi et al., 2016; Kovac et al., 2016; Sandstrom et al., 2019). This category comprises several groups of characteristics:

- **Tree size and density**. These basic characteristics of forests correspond to tree measurements and can be provided at stand (basal area, density) or population level (size classes) (Alberdi et al., 2016; Pescador et al., 2022). They represent a snapshot of forests at any given time although they change over time, i.e., between successive surveys. They overall describe key forest processes (e.g., primary production) and functional characteristics. They can be applied to specific tree species, which will likely be characteristic of the habitat.

- **Canopy cover**. These characteristics describe basic features of forests that denote habitat continuity at the site or microsite level (Marín et al., 2021). It addresses the whole assembly of growing trees, considering specific tree species, which will likely be characteristic of the habitat, or individual trees, whose health status can be evidenced by decay/defoliation.
- **Vertical structure**. These key structural characteristics are determined by the various forest layers. They include tree height and also distinct strata: trees, shrubs, herbs, bryophytes and lichens. In general, good forest condition is assessed on the basis of an adequate, diverse stratification (Kovac et al., 2016; Pescador et al., 2022), while overgrowth in a single stratum (or a few strata) may denote human-induced alterations (canopy opening, disturbances, nitrification).
- **Horizontal structure**. These characteristics describe forest homogeneity vs heterogeneity throughout the space, at site level (i.e., excluding landscape-level characteristics) (Kovac et al., 2016). They are usually assessed on the basis of vegetation and tree canopy cover (or coverage), which is particularly important in forests. Related variables (from percentage to spatial distribution) are often applied to tree species or to functional or growth forms, which may correspond to characteristic species of the habitat, but also to ground cover. At site level, the horizontal distribution of canopy and gaps often determines the regeneration of many plant species, especially tree species.
- **Large and old trees**. Although there is generally a rough correlation between tree age and tree size (size is often considered a proxy of age), these two characteristics denote somewhat distinct values. The occurrence and abundance of old trees is a key characteristic of good forest condition (Alberdi et al., 2016), since this often denotes a high maturity (Mosseler et al., 2003; Wirth et al., 2009; Burrascano et al., 2013), and in many cases is associated with a limited impact of large disturbances over time. Large trees, provide microhabitat and, if these are old trees, they indicate a continuity of such microhabitats over time. They are therefore, in general, indicators of the satisfactory functioning of forests. Thus, these characteristics are also related to functional and dynamical categories.
- **Deadwood**. The occurrence and abundance of deadwood (also known as debris or dead trees), and its different sizes and stages of decomposition (which determine deadwood quality), is an important characteristic of good forest condition (Kovac et al., 2016; Sandstrom et al., 2019) particularly when associated with advanced successional stages (Wirth et al., 2009; Burrascano et al., 2013), during which old-tree mortality occurs. Deadwood provides a microhabitat for other species, especially animals and fungi, and plays an important role in nutrient and carbon cycles (Stokland et al., 2012). Deadwood may also result from natural disturbances or active forest ecosystem restoration measures. Thus, such good condition may not apply if the high volume of deadwood is due to recent, intense disturbances that are not part of the natural disturbance regime.
- **Microhabitats**. They correspond to particular structural features, such as cavities in stems, which provide habitat for other species (Alberdi et al. 2016), in particular for animals and fungi. This group of variables includes a variety of characteristics, often associated to specific habitats (e.g., hummocks around trees), or to horizontal (e.g., open patches) and vertical structure. For grouping purposes, deadwood-related microhabitats are considered in the previous group.

Functional

These characteristics refer to the set of interactions between the biota and the environment that determine the regulation of energy and matter flows. This category comprises several groups of characteristics:

- **Key processes**. There are various processes that determine forest functioning. The outcome of these processes can be directly estimated in some characteristics, such as those related to **primary production** (Maes et al., 2023) and **growth** (Bastrup-Birk, 2014). Alternatively, the condition of the habitat can be inferred through the characteristics of the biota involved in such processes, which are typified as **functional groups** (Messier et al., 2019). In forests, the functional traits of species often correspond to tolerance or response to conditions and resources (e.g., shade-tolerant species, deciduous species). The functional diversity of biota has been shown to be important for the regulation of ecosystem functioning and for enhancing resilience against detrimental stressors and disturbances (Schmitt et al., 2020). Current databases of the functional traits of species allow compositional characteristics to be linked to functional diversity.
- **Biotic interactions**. Functional characteristics directly related to biotic interactions which, in forests, correspond particularly to herbivory (Alberdi et al., 2016) and decomposition. These, in turn, are associated with structural variables such as deadwood.
- **Canopy health**. Characteristics that usually denote signs of undesirable condition of forests due to intense environmental (defoliation) or biotic (e.g., leaf consumption, insect-induced dieback) impacts (Alberdi et al., 2016; Kovac et al., 2016) that do not correspond to the natural regime.
- **Human-induced impacts**. These characteristics describe the impact of human activity on forest functioning and usually correspond to a loss of habitat condition (Alberdi et al., 2016; Marín et al., 2021). There is a great variety of human-induced activities, often associated with silviculture, grazing and agricultural uses, and outdoor recreation. Management actions aimed at improving habitat condition and restoration should be considered when assessing these variables.

With regard to functional characteristics, **dynamical characteristics** refer to the continuity of the different successional stages, e.g., the ability to appear, regenerate or remain after disturbances, or to transform the habitat type into a different type. They are related to functional characteristics, though in forests they acquire distinctness by explicitly referring to the temporal dimension of change (e.g., succession), and they commonly comprise demographic characteristics. This category consists of several groups of characteristics:

- **Age**. This characteristic usually refers to a stand property and may correspond to the estimated age of trees or to age class structure. It is considered a dynamical characteristic since it reflects the historical period during which the stand has evolved. However, in some cases it may overlap with structural characteristics such as the occurrence of large/old trees, and is also associated with tree size and density (Wirth et al., 2009). Overall, it can potentially be considered to determine habitat condition since it indicates a period without stand-replacing disturbance. However, given its overlapping with some structural characteristics and the difficulty in estimating it, its use as a variable for determining habitat condition is reduced.
- **Regeneration**. This characteristic refers to the young stages of a tree's life history. It is key to ensuring the permanence of the forest or, alternatively, it determines the feasibility of its successional trajectory. It may be assessed in a general way, but it implicitly applies to the

characteristic and typical tree species of the forest habitat (Alberdi et al. 2016; Kovac et al., 2016).

- **Disturbance regime**. This characteristic potentially includes the cause, extent, intensity and frequency of the set of disturbances that affect forests. In intermediate regimes, resilience is effective and disturbances can be considered a regular component of forest dynamics, from stand-replacing to large landscape scales, enhancing nutrient cycling and promoting biodiversity, e.g., by gap dynamics (Spies, 2004). Thus, forest condition assessment should evaluate whether this characteristic has a negative impact, as do many human-induced impacts, or is a component of forests naturalness (Bengtsson et al., 2000).
- **Succession**. This characteristic refers to forests as a dynamical system, which is not expected to remain static indefinitely. Favourable condition should account for the natural dynamics of forests (Perry, 2008), which comprise the classic successional stages (gaps with herb and shrub dominance, secondary forests with an even-aged/size structure, and old, mature forests with an uneven-aged/size structure); that is, imbedded in gap and landscape dynamics, associated with some degree of disturbance corresponding to a natural regime (i.e., not strongly determined by human impact). The variables used for assessing forest condition may vary according to habitat.

Landscape characteristics

Landscape characteristics refer to forest distribution throughout the space. Importantly, the landscape characteristics of a single habitat should be assessed in the context of the surrounding habitats in order to obtain a comprehensive insight. For example, considering a balanced mosaic of forest and grassland-type habitats may provide an overall more positive condition assessment than one derived from considering the habitats in isolation. Importantly, these characteristics should be assessed at large spatial scales that usually go beyond a single location. This category comprises several groups of characteristics:

- **Patch size**. Forest extent is an important ecosystem characteristic for maintaining populations (e.g.., by dispersal and gene flow) and ecosystem processes (e.g.., water and nutrient fluxes). Therefore, forest patch size is a relevant variable for determining forest condition. In general, large patches are associated with a favourable condition (Marín et al., 2021), though different metrics can be applied (Kovac et al., 2016). The assessment of forest habitat conditions often accounts for patch size trends over time. However, forest patch size offers a poor description of forest condition without also assessing other compositional, structural and functional characteristics.
- **Fragmentation**. This characteristic refers to the loss of continuity of forests throughout the territory. Thus, it implicitly corresponds to a loss of forest extent and integrity. In general, it implies a decrease in favourable condition (Bastrup-Birk, 2014; Maes et al., 2023), since the continuity of forests favours the maintenance of the ecosystem functionality (e.g., water and nutrient fluxes) throughout the territory. Complementarily, connectivity is important for species dispersal, determining metapopulation dynamics However, connectivity may also lead to the propagation of disturbances (e.g., wildfires) or biotic stressors (e.g., alien species invasion, pest outbreaks). Thus, a negative relationship between fragmentation and biodiversity is not always found. Fragmentation is narrowly related to patch size, and a variety of metrics can be applied. For example, compactness refers to percentage of core areas, i.e., the interior of forest patches, excluding the perimeters (Kovac et al., 2016; Marín et al., 2021). With regard to other landscape-level characteristics, it is important to assess the fragmentation of forests at large spatial scales in order to encompass the entire landscape matrix.

Table 2. Ecological characteristics and selection of variables to measure forest habitat condition

Ecological characteristics	Types	Description of associated variables	Examples of variables
Abiotic characteristics	**Physical state characteristics**	Physical descriptors of abiotic variables which determine forest ecosystem condition. They include variables related to temperature, precipitation, radiation, physical soil characteristics, water regime	- Erosion (Pescador et al. 2022) - Bare soil (Pescador et al. 2022) - Water content (NDWI proxy) (Maes et al. 2023) - Water regime within historical range (riparian and bog forests)
	Chemical state characteristics	Chemical descriptors of abiotic variables which determine forest ecosystem condition, particularly regarding soils. They include pH, nutrient content and soil matter content	- Soil organic matter (Maes 2023) - Soil nutrients (N, P) - Soil acidity (pH)
Biotic characteristics	**Compositional state characteristics**	Assembly of species constituting the forests (i.e., composition / diversity of ecological communities at a given location and time). They include species richness, alien species, characteristic species, typical species, and harmful species	- Abundance of typical species (Wulf 1997) - Tree species richness (Alberdi et al. 2016; Marín et al. 2021) - Shrub species richness (Pescador et al. 2022) - Number of species with suitable habitat (naturalness) (Bastrup-Birk et al. 2014; Marín et al. 2021) - Species richness of threatened forest birds (Maes et al. 2023) - Mammal, birds and amphibians abundance and composition (Brown et al. 2020) - Abundance of alien species (Alberdi et al. 2016)
	Structural state characteristics	Pattern of space occupancy, (i.e., aggregate properties mostly referred to biomass-related biotic components) (e.g., total biomass, canopy coverage, annual maximum NDVI). They include Tree size and density, canopy cover, vertical and horizontal structure, large/old trees, deadwood microhabitats	- Canopy cover (Marín et al. 2021; Maes et al. 2023) - Canopy height (Pescador et al. 2022) - Standing volume (Kovac et al. 2016; Pescador et al. 2022) - Stand basal area (Kovac et al. 2016) - Horizontal distribution of development stages (Kovac et al. 2016) - Vertical distribution of canopy layers (Kovac et al. 2016) - Tree size (height, diameter) classes (Alberdi et al. 2016; Pescador et al. 2022) - Abundance of old and large trees (Mosseler et al. 2003; Alberdi et al. 2016) - Deadwood volume and quality (Burrascano et al. 2013; Kovac et al. 2016; Sandstrom et al. 2019) - Presence of tree microhabitats (Alberdi et al. 2016)

Ecological characteristics	Types	Description of associated variables	Examples of variables
	Functional state characteristics	Set of interactions between the biota and the environment that determine the regulation of energy and matter flows interactions between the main ecosystem compartments. They include primary production and growth, biotic interactions, and canopy health. Dynamical characteristics referring to inherent temporal changes of the habitat, such as successional stage, are considered here. They include age, regeneration, disturbance regime, succession. Human-induced impacts are also included here. They include silviculture, plantations, and human frequentation	- Forest biomass (Marín et al. 2014) - Growing stock (Bastrup-Birk 2014) - Forest productivity (NDVI proxies) Maes et al. 2023) - Tree functional diversity (Messier et al. 2019) - Gaps in forest canopy (Mosseler et al. 2003) - Browsing damage (Alberdi et al. 2016) - Occurrence of disturbances (Alberdi et al. 2016 - Regeneration (type), recruitment (share of basal area) (Alberdi et al. 2016; Kovac et al 2016) - Share of damaged, defoliated trees (Kovac et al. 2016) - Tree pests and diseases (Alberdi et al. 2016)
Landscape/ seascape characteristics		Metrics describing forest distribution over the space, i.e. mosaics of forest habitats at landscape scale. They include patch size, fragmentation, structural and functional connectivity	- Forest patch surface (Kovac et al. 2016; Marín et al. 2021) - Connectivity (Bastrup-Birk 2014; Maes et al. 2023) - Width and longitudinal continuity of riparian vegetation (riparian forest)

Box 1. Examples of indicators of forest maturity and good condition (Pescador et al. 2019a)

1. Vertical diversification, considering three main strata of the trees delimited into three fractions that occupy 1/3 of the height of the main canopy (dominant height).
2. Gaps in the canopy, caused by the fall or death of individual trees or small groups.
3. Advanced regeneration, small, established individuals (e.g., 2.5 - 7.5 cm. DBH).
4. Large trees, extremely thick diameter, corresponding to advanced successional stages with an age close to the limit imposed by their longevity.
5. Irregular mass structure, i.e. balanced distribution of dimensional classes.
6. High tree biomass (generally measured through specific volume formulas), related to the existence of old, large trees, although it greatly depends greatly on the dominant species and the climatic and edaphic environment.
7. Dead wood, both standing and decaying on the ground, in relevant quantities.
8. Tree microhabitats (holes, crevices, polypores, etc.), which are of great importance for biodiversity.
9. Tree and shrub richness within the dominant tree canopy, inform about plant and microhabitat diversity.
10. Absence of recent anthropogenic interventions.

1.3 Selection of typical species for condition assessment

Typical species of the habitat are used to assess whether a habitat has favourable conservation status (FCS). According to the guidelines for reporting under Art. 17 of the EU Habitats Directive (European Commission. DG Environment, 2023), typical species should be those that **occur regularly** at a high constancy in a habitat type, or at least in a major subtype or variant of a habitat type, and should include species that are **good indicators of favourable habitat quality**, e.g., by indicating the presence of a wider group of species with specific habitat requirements. Therefore, **species sensitive to changes in the condition of the habitat** (early warning indicator species) should be included. Moreover, typical species should **provide useful additional information**, assuming that the habitat's composition, structure and function are already being monitored.

Thus, **typical species should be distinguished from characteristic species**, which are used to identify the habitat type according to the Interpretation Manual of EU Habitats (which provides a formal list of characteristic species for each habitat). In this respect, the concept of 'typical' species used for habitat assessment (DG Environment, 2023) differs significantly from the concepts of the phytosociological approach, since they are not strictly focused on the species' diagnostic value (**diagnostic** species are those that occur regularly in the habitat type and are therefore used to identify habitat types).

Typical species may be drawn from any species group. In addition to vascular plants, the most commonly selected group, bryophytes, lichens, fungi and animals should also be considered. Many important functions such as dispersion, pollination and decomposition, rely mainly on both vertebrate and invertebrate species, and their exclusion may lead to incomplete assessments of habitat function and structure.

Forests simultaneously provide animals with food, shelter, reproductive opportunities and protection from predators. Thus, a wide range of animal species that depend on forest habitats could be considered as typical species for forest conservation assessment. Some mammal species (e.g.., forest bats, squirrels, martens, etc.), birds (e.g., woodpeckers), amphibians (salamanders, toads), reptiles (lizards, snakes) and/or insects (*Hemiptera, Isoptera, Orthoptera, Thysanoptera, Coleoptera, Diptera, Hymenoptera, Lepidoptera, Raphidioptera*) are appropriate for consideration (Canterbury et al 2001; EUROPARC-España 2017).

Another approach for selecting typical species for assessing the conservation status of forest types is to use **keystone species**. Keystone species play critical ecological roles in forests, even when not especially abundant. Thus, they have a disproportionate impact on the organisation of the habitat in relation to their number or biomass. The loss of a keystone species can have major consequences for the community. Most keystone species can also be used as indicators of the absence/presence of disturbances (early warning indicator species). Some keystone species used as typical species for assessing the conservation status of forest types are: *Carpinus betulus, Quercus spp., Pinus cembra, Pinus spp., Juniperus spp., Sphagnum spp.* and *Cladonia spp*.

Finally, some groups of species can be used as **indicators of ecological conditions**, depending on their autecology, e.g., thermophilous and calciphilous plants and animals such as salamanders, which are sensitive to soil condition which, in turn, is determined by the structure and composition of the shrub and forest canopy.

Similarly, the density or biomass of understory foliage can be positively correlated with food availability for birds and small mammals (Brown et al., 2020). In addition, some animals play a crucial role in forest functions such as dispersion, nutrient recycling, etc. For example, oak forests rely heavily on rodents and birds for seed dispersion (Sunyer et al., 2013). Finally, fungi species can be used as indicators also; e.g., the presence/absence of saprotrophic (*Trametes sp., Pleurotus sp*.), parasitic (*Armillaria*) and mycorrhizal (*Boletus spp., Tricholoma spp.*) fungi may provide valuable information about the conservation status of forest habitats.

As a summary, Table 3 provides an illustrative list of species groups that can be used as indicators for assessing forest condition, since their responses reflect changes in various forest attributes, from canopy cover and deadwood abundance to soil health and air quality. Monitoring a combination of these groups of species can provide a comprehensive understanding of forest condition and health.

Table 3. Illustrative list of species groups that can be used as indicators to assess forest condition, including their ecological roles, sensitivities and indicator meaning

Species Group	Ecological role	Sensitive	Indicators
Mammals	keystone species in forests, affecting seed dispersal, predator-prey dynamics, and herbivory	to forest fragmentation, hunting pressure, and availability of shelter and food	human disturbance and habitat fragmentation
Bats	insect pest control, pollination, and seed dispersal	to canopy cover, roost availability, and food resource changes	forest disturbance, particularly logging and fragmentation
Birds	seed dispersal, insect population control, and nutrient cycling	to habitat structure, tree species composition, and forest fragmentation	changes in canopy cover and forest understory conditions
Woodpeckers	insect pest control. They create nesting cavities that are used by other species	to the availability of deadwood and large trees. Logging and deadwood removal	old-growth forest conditions
Reptiles	control insect pest and small mammal populations control	to changes in microhabitat, sunlight exposure, and habitat structure	changes in canopy density and forest floor complexity
Amphibians	insect pest control. Food source for some predators. Contribute to nutrient cycling on moist forest floors.	highly sensitive to changes in soil moisture, pollution, and microclimate changes due to canopy loss	forest degradation and climate changes
Butterflies and Moths	pollinators. Food source for birds and other predators.	to plant species diversity, climate, and microhabitat conditions.	floral diversity and microclimate changes
Beetles (stag beetles, jewel beetlesa, etc.)	nutrients recycling (they decompose wood and leaf litter). Predatory beetles help control insect pest populations	to logging, pollution, and changes in deadwood abundance	forest structure and deadwood availability
Ants	ecosystem engineers, affecting soil structure, decomposition, and nutrient recycling. Insect pest control	to soil and leaf litter conditions, moisture, and forest floor composition	habitat disturbance and soil health
Earthworms	soil aeration, mixing, and nutrient cycling. Enhance soil structure, promoting root growth and water retention	to soil quality, moisture, and pollutants, including heavy metals and pesticides	soil health and integrity

Species Group	Ecological role	Sensitive	Indicators
Trees and shrubs	key stone for structural and functional properties of forests, determining primary production and food webs, and providing habitats	to disturbance regime, and climate change	forest structure, habitat disturbance, climate change adaption (native trees)
Herbs	provide habitat for animals. Contribute to nutrient cycling and soil stabilization	to light levels, humidity and disturbance regime	forest structure, habitat disturbance, animal biodiversity
Bryophytes	help retain soil moisture, prevent erosion, and provide habitat for small invertebrates	to humidity, air pollution, and light levels	logging, which alters canopy cover and humidity
Lichens	provide habitat for small invertebrates. Contribute to nutrient cycling and soil stabilization	to air quality, light, and soil moisture	pollution levels, especially sulphur dioxide and nitrogen compounds
Fungi	mycorrhizal fungi form symbiotic relationships with tree roots, aiding in nutrient uptake. Decomposer fungi recycle nutrients from dead organic matter	to soil composition, pollution, disturbance regime, and tree species composition	soil and tree health, and forest maturity

Rosalia alpina, Domogled-Valea Cernei National Park, Romania.

Given the broad significances of typical species and the particularities of the different habitats, several considerations should be appraised:

a) the criteria and procedures for selecting typical species for forest habitats differ depending on the characteristics of the habitat types.
b) the list of typical species chosen for the purpose of assessing conservation status should remain stable over the medium to long term (Angelini et al., 2018).
c) the set of typical species for a habitat type should consider the diversity (all subtypes) of the habitat across its range; so, typical species can vary across the habitat range.
d) typical species do not need to be exclusive of one habitat type; some typical species could be shared by more than one habitat.
e) typical species should provide complementary information about other variables that characterise habitat condition, irrespective of species identity. This is particularly relevant for structural variables, which largely rely on dominant typical species. Consequently, these species should be considered size-sensitive indicators. In contrast, keystone typical species provide additional information that is not so dependent on the scale of work, and are often referred to as presence/absence species. Therefore, evaluation should be carried out at the local scale (monitoring plot/station) by assessing presence and abundance, and the overall assessment at a higher scale should consider the number of localities in which the species are present.

Though it may seem advisable to carry out the condition assessment based on typical species separately to the structure and function assessment, rules are needed to integrate both. This will require ranges (e.g., frequency or abundance) to be defined according to the species' ecology and the area of the habitat or the number of localities. Since Art.17 of the EU Habitats Directive states that the occurrence of typical species should guarantee the conservation of viable populations of the species within their distribution area, the assessment of typical species should consider their frequency, abundance and distribution (e.g., presence in a minimum number of localities).

Dendrocopus medius

2. Analysis of existing methodologies for the assessment and monitoring of habitat condition

Methodologies for assessing and monitoring the condition of forest habitat types have been compiled from 24 EU Member States (see references in Annex 1).

Most of the MSs share a common methodological approach for all forest habitats in their country. However, some countries have distinct or specific methods for some particular habitats, in particular for riparian forests and bog woodlands.

The scope and degree of completeness and development of the methodologies vary among the MSs. Some have methodologies covering a relatively complete selection of variables with well-defined metrics, measurement methods and thresholds for condition assessment, while for other MSs the definition or development of these elements is incomplete.

2.1 Variables used, metrics and measurement methods, existing data sources

According to the environmental and ecological characterization of forest habitats (Table 1) described in section 1.2., the used variables can be grouped as described in Table 4.

Most forest habitats share common characteristics and the variables used to assess their condition. However, riparian forests, bog woodlands and wooded dunes have certain features that are translated to the selected variables, as detailed below. Despite this commonality, only a few MSs (Hungary, Italy, Lithuania, Poland, Spain) use the full set of variables of the SEEA Ecosystem Condition Typology (ECT) (abiotic, compositional, structural, functional and landscape).

The analysis shows that the most commonly-used variables are biotic, in particular compositional and structural variables, which are included in the methodologies available from all the MSs considered in the analysis. Characteristic species is the most common variable among the compositional characteristics, and deadwood is the most common among the structural characteristics. Non-alien and harmful species, and alien species among the compositional characteristics are also used by almost all the MSs. Regeneration and human-induced impacts are the most commonly-used variables in relation to functional characteristics.

Abiotic variables are rarely used in the assessment of forest condition, and are mainly focused on soil characteristics and some variables directly determining specific habitats, such as water regime in riparian forests. In fact, soil characteristics are poorly assessed in general, which is possibly due to the fact that collecting this information is costly and laborious given the large number of surveyed plots. As a result, in several countries soil characteristics are indirectly, qualitatively assessed according to species composition.

Table 4. Classification of variable groups, according to the environmental and ecological characterisation of forest habitats (SEEA ecosystem condition typology (ECT)), indicating Member States that have included them in their methodologies for assessing forest habitat condition

AT: Austria, BE: Belgium, BG: Bulgaria, CZ: Czech Republic, DE: Germany, DK: Denmark, ES: Spain, FR: France, GR: Greece, HU: Hungary, IE: Ireland, IT: Italy, LV: Latvia, LT: Lithuania, NL: Netherlands, PL: Poland, RO: Romania, SK: Slovakia, SL: Slovenia

Ecological characteristics	AT	BE	BG	CZ	DE	DK	ES	FR	GR	HR	HU	IE	IT	LT	LV	NL	PL	RO	SK	SL
1. Abiotic characteristics																				
1.1 Physical state characteristics																				
Light condition						■														
Water regime	■		■			■				■				■	■	■	■			■
Soil characteristics					■	■	■		■				■				■			
1.2 Chemical state characteristics																				
Soil nutrients						■	■										■			
Soil pH						■	■										■			
2. Biotic characteristics																				
2.1 Compositional state characteristics																				
Characteristic species (plants)	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■
Animal species							■				■		■		■					■
Species richness		■	■		■		■						■		■		■			■
Alien species		■			■		■	■				■	■	■			■			
Native harmful species		■					■		■		■	■		■	■		■			

Ecological characteristics	AT	BE	BG	CZ	DE	DK	ES	FR	GR	HR	HU	IE	IT	LT	LV	NL	PL	RO	SK	SL
2.2 Structural state characteristics																				
Tree size classes	■				■		■					■	■		■	■				
Canopy cover			■				■		■		■	■			■				■	■
Vertical structure	■	■		■		■	■	■				■	■				■	■		
Horizontal structure	■	■		■		■	■		■			■	■				■	■		
Large/old trees	■	■	■			■	■	■			■	■		■	■		■		■	
Deadwood	■	■	■	■	■	■	■	■	■		■	■	■	■	■		■		■	■
Microhabitats						■							■		■		■			
2.3 Functional state characteristics																				
Key processes		■	■			■			■						■		■		■	
Biotic interactions							■	■					■							
Canopy health							■								■		■		■	
Human-driven impacts		■		■	■	■	■	■				■	■	■	■		■		■	
Age			■										■	■	■		■		■	■
Regeneration							■	■	■		■	■					■		■	
Disturbance regime		■					■		■		■		■	■						
Succession		■	■						■				■		■		■			
3. **Landscape characteristics**																				
Extent	■	■	■										■				■			
Fragmentation	■					■		■			■		■	■		■	■			

Box 2. Examples of selected variables from national methodologies available

The variables used by MSs for reporting forest habitat condition have been classified according to the SEEA Ecosystem Condition Typology (abiotic, compositional, structural, functional and landscape). Only one representative example of variable per MS and variable type is shown.

Hungary

Ecological characteristics	Example variable	Measurement	Effect on habitat condition	
A-Abiotic	rate of soil erosion	categorical (strongly negative, negative, neutral, positive)	negative	field expert judgement
B1-Compositional	invasive alien species	cover (%)	negative	field survey, reference list
B2-Structural	large trees	number of specimens above a given DBH ha-1	positive	field survey
B3-Functional	natural disturbances	possible impacts by native animals (ants, rodents, herbivores)	positive/ negative	expert judgement
C-Landscape	fragmentation	distance (m) to the similar habitats	negative	not available (1)
A-Abiotic	rate of soil erosion	categorical (strongly negative, negative, neutral, positive)	negative	field expert judgement

Italy

Ecological characteristics	Example variable	Measurement	Effect on habitat condition	
A-Abiotic	litter	cover on the ground (%)	positive	vegetation survey
B1-Compositional	typical species	abundance (Braun-Blanquet scale)	positive	vegetation survey
B2-Structural	layers (trees, shrubs and herbaceous)	cover (%)	positive/ negative	vegetation survey
B3-Functional	maturity	biological spectrum as an indicator of maturity (including epiphytes, lianas and climbers).	positive	field survey
C-Landscape	patch size	ha	positive	GIS analysis
A-Abiotic	litter	cover on the ground (%)	positive	vegetation survey

Lithuania

Ecological characteristics	Example variable	Measurement	Effect on habitat condition	
A-Abiotic	drying systems	narrative (drainage ditches, water level, flood regime nature) [2]	negative	field expert judgement
B1-Compositional	expansion of native herbaceous plants	cover (%)	negative	field survey, reference list
B2-Structural	dead trees	categorical (0-none, 1-single, 2- sparse, 3-moderately, 4-abundant)	positive	field survey
B3-Functional	logging impact	narrative (methods, intensity, and period) [2]	negative	field expert judgement
C-Landscape	habitat homogeneity	proportion of area occupied by the habitat in transects	positive	not available[1]
A-Abiotic	drying systems	narrative (drainage ditches, water level, flood regime nature) [2]	negative	field expert judgement

Spain

Ecological characteristics	Example variable	Measurement	Effect on habitat condition	
A-Abiotic	soil organic matter	thickness (cm)	positive	National Forest Inventory
B1-Compositional	shrub richness	number of shrubs species per plot (ha-1)	positive	National Forest Inventory
B2-Structural	basal area	m2 h-1	positive	National Forest Inventory
B3-Functional	regeneration density	number of specimen's diameter < 7.5 cm, weighted by development category ha-1	negative	National Forest Inventory
C-Landscape	functional fragmentation	Orlóci dissimilarity index	negative	GIS spatial analysis (Spanish forest habitat map)

Although most of the MSs use field surveys as the basic procedure for obtaining information about the species (except for landscape variables, for which cartography and GIS analysis is the rule), the specific metrics and measurement methods vary widely between the MSs, and therefore also differ between habitats across the geographical gradient. Quantitative and semi-quantitative measures are the rule in these field surveys (e.g. for counting or measuring specimens, identifying and estimating cover of layers or regeneration categories). A number of the MSs obtain this field information from National Forest Inventory systems, though poorly represented habitats may require an additional, specific survey. Expert judgement is also commonly employed in field surveys (e.g. by applying phytosociological methodologies, estimating natural disturbances and human-induced impacts), and in the building and interpretation of reference lists for certain compositional variables (characteristic species, alien and native harmful species).

Physical and chemical variables

Physical variables are used rather infrequently (by only 13 MSs out of the countries considered in this analysis), as are chemical variables (by only 3 MSs). Among these, soil characteristics are measured by some MSs (e.g. soil thickness, texture, rockiness, erosion). Water regime variables (water level in watercourses, groundwater level, flood height, flood period), in particular, are frequently used for riparian forests. Among the **chemical variables**, the following are included in the methodologies available from some MSs: soil pH, soil nutrients, organic matter, plant litter, mulch, soil acidity, soil base saturation and phosphorus, carbon and nitrogen content in the soil.

Compositional variables

Forest habitats are mostly assessed using compositional variables, particularly those related to the presence or abundance of **species that are characteristic of the habitat**, which often correspond to diagnostic or dominant species, key species in ecological processes, or typical species (sensu Habitats Directive). In fact, these variables are present in the methodologies available from all the MSs considered in this analysis.

Habitat condition is commonly established by the record of occurring species lists (e.g. Belgium, Denmark), species frequency or abundance (e.g. biovolume in Spain, percentage of trees in Poland, percentage of ground cover in Bulgaria, Braun-Blanquet scale in Czech Republic), which are usually contrasted against determined species or lists of species (e.g. by number of species in Belgium). Although it should correspond to the description of each habitat type, with trees having a relevant role, there is usually a lack of accurate information about the criteria for determining these species and the procedures used for contrasting against reference lists. Imprecise descriptions (e.g. “key, target or valuable species”) are not useful for assessing the significance of these species and how they change throughout the European territory.

There is also a disparity in the criterion of using species abundance or simply recording species occurrence. Although many of these methodologies are focused in particular on tree species composition, understory layers (including shrubs and herbs) are also commonly monitored. In fact, indicator species of specific habitats, such as bryophytes, lichens and calcicolous plant species, are sometimes considered.

In addition, combinations of certain species that characterize phytocoenological categories are considered by several of the MSs. Finally, animals are also recorded, (though only in 5 MSs) but, in general, only general indications are provided about what is measured, e.g., the description of the variable corresponds to the “presence of vertebrate species of special interest”, “animal species present”, “remains and traces from mammals and birds. Noticeably, saproxylic insects, which are considered as indicators of deadwood volume and forest maturity (Lachat et al., 2012), are recorded in 2 MSs.

The second most commonly-used compositional variables are the presence or cover of **alien** or **harmful species**. These two types of species should be distinguished since, although both types of species tend to increase in disturbed habitats, they frequently respond to different processes of habitat degradation. Alien species are always of anthropogenic origin and are often the result of forced introductions. Moreover, they are generally listed and regulations exist to control them, especially in protected areas. In contrast, harmful species are often native species that grow expansively in altered habitats due to specific disturbances such as eutrophication (e.g. coverage of nitrophilous taxa), and/or negatively impacting species or characteristic processes of the habitat (e.g. presence/absence/low cover of ruderal and expansive native species), thus constituting valuable indirect indicators of poor condition.

However, in some of the MSs and for some forest habitats they are not well distinguished in the reported methodologies, possibly because their consequences may converge (i.e. many harmful species are alien and most alien species are considered harmful). The wide range of methodologies used to estimate these variables denotes different approaches. Alien species are commonly recorded according to reference lists, and different metrics (e.g. presence, abundance) can be applied, sometimes referred to forest layers, especially the understory.

The identification of harmful species shows a variety of taxonomic (e.g. *Rubus* spp.) and functional (e.g. nitrophilic) criteria, which denotes species with a recognized capacity to expand, which should not occur in the habitat; but these are generally broadly described in terms of unspecified, negative effects (e.g. negative expansive species, negative indicator species).

Species **richness** is used less explicitly, although implicitly it is considered through the inventory of characteristic species, often from a list of key species provided for each habitat type (e.g., presence, number and cover of characteristic, key, typical, dominant or positive species in the tree and shrub layer). In other cases, species richness is implicit when referring to species number or abundance of perennials, trees, shrubs, ferns and fauna in functional groups (e.g., tree and shrub species richness (available from national forest inventories), abundance of shade-tolerant species; abundance of ferns in riparian forests), or biogeographical (endemic) groups. However, the rationale behind the selection of these sets of species is not commonly available. More complex diversity indices considering species abundance (e.g. Shannon, Simpson's) are rarely used.

Structural variables

Among the structural variables, **deadwood** is a key variable for characterizing forest habitat condition. Although there is an appreciable consistency in the wording of the deadwood variable, the methodologies for estimating it show some disparity, ranging from presence to more quantitative estimations. The volume of deadwood is measured in m3/ha in four MSs and the volume of thick deadwood (i.e. a number of specimens with a minimum size – greater than a certain diameter and length) and dead trees are also included in the assessment by 15 MSs. The proportion of deadwood (volume of deadwood relative to total volume of wood) is used by 2 MS, and the presence of deadwood by 1 MS.

Large trees − which are often not distinguished from old trees, since age is much more difficult to estimate than size − are included in a significant number of the methodologies employed by several of the MSs (12) as a criterion of good condition, availing of the information provided by regular forest inventories. As with deadwood, the abundance of large trees is considered a good indicator of forest maturity and low intensity and frequency of disturbance. However, it is noteworthy that the specific recognition of microhabitats other than deadwood is rarely considered, despite their significance for biodiversity.

Other structural characteristics, such as **vertical structure**, are also commonly considered, but again there is a significant variability in the specific parameters measured in the methodologies employed by the MSs. In fact, the vertical structure variables comprise a wide variety of parameters, including the presence of different layers, the height of specific layers (e.g. canopy, herbs), or unspecified descriptions of vertical structure.

Horizontal structure is also commonly used to assess forest habitat condition. As with vertical structure, this group encompasses a heterogeneous range of variables, including general coverage, coverage of species in specific layers, and even coverage of phenological phases. Interestingly, some basic features of the structural forest characteristics, such as canopy cover, basal area or tree density, are not universally considered, possibly because they are considered within certain coverage-related variables included in horizontal structure, or because not all of the MSs use methodologies based on regular forest inventories, in which dasometric variables (based on tree size) are measured. Again, the disparities in the methodologies used by the different MSs make it difficult to assess forest conditions across the European territory.

Functional variables

Variables describing forest dynamics, which can be considered closely related to functional characteristics, are not widely used, apart from **regeneration** to some extent (present in 7 of the MSs). This variable provides important insights on the future fate of the habitat (in relation to gap dynamics) and its resilience to certain types of disturbance. However, it is not universally estimated, particularly in methodological procedures that are mainly based on compositional characteristics. The methodologies used to estimate regeneration are usually not well detailed and remain qualitative, possibly due to the time-consuming effort needed to quantify recruits. Moreover, it is often species-specific, focusing on the recruitment of characteristic species of the habitat.

The structure of **age classes** is another important variable describing forest dynamics, but it is not commonly employed in the methodologies, although 7 of the MSs consider stand age and other related variables (e.g. mean age of stock, mean and maximum age in years of the canopy trees, age of the oldest trees in the stand, age classes of characteristic species). Alternatively, it is derived from tree size classes or, more specifically, from large trees, which are considered structural variables.

Other features related to forest dynamics, such as **disturbance regime** - which encompasses wildfires and a variety of perturbed situations not directly caused by humans - are not very widely considered. Surprisingly, indicators of a key process in forest dynamics, such as the succession stage, are very rarely considered, and their description and meaning are uncertain.

Other functional variables are less represented in the assessment of forest habitat conditions, apart from **human-induced impacts** on the regular disturbance and biotic interactions regime. This category includes various anthropogenic influences on the forests, such as those resulting from silviculture, harvesting and grazing (and, less frequently, drainage), in addition to undetermined impacts (degradation, deterioration, damage). Thus, different types of data collection methods, measures, thresholds and evaluation procedures are used to estimate them. While it is obvious that these impacts threaten habitat conditions and may be related to pressures, indicators of attributes that ensure the adequate functioning of forests, such as functional diversity or biotic interactions, are scarcely used. In fact, symptoms of poor canopy health that are not related to direct human-induced impacts are rarely considered. Among the latter, defoliation, pests, impacts from beaver activity, and visible natural disturbance (windfall, insect damage) are proposed in the methodologies used by 4 of the MSs.

Landscape variables

Landscape-related variables - overall describing habitat patch size and fragmentation - are not universally recognized in the methodologies employed by the MSs, likely because they are addressed in the surface assessment of the habitats. Among them, fragmentation variables, which are related to connectivity, are measured using different methodologies. For instance, a methodology to assess forest habitat fragmentation at the biogeographical region scale based on the pattern of the relationship between the cumulative frequency of the number of patches and their sizes is available from Spain (Del Barrio et al., 2019). Criteria related to favourable spatial configuration to maintain sustainable populations of the characteristic species are important in the assessment of some MSs (e.g. Belgium-Flanders).

Variables for specific forest habitats

In addition to the common variables for all forest habitats, those used for assessing the condition of **riparian forests** include abiotic variables, such as water regime (4 of the MSs). For example, for habitat type 91F0, Croatia has up to 4 water regime variables, including flood height, groundwater level, number of days for each flood period and water level in major watercourses. In the case of **bog woodlands**, specific variables include abiotic variables related to the water regime. Finally, in **wooded dunes**, variables related to human-induced impacts are more often considered.

2.2 Definition of ranges and thresholds to obtain condition indicators

In general, the criteria for establishing thresholds that determine the condition of habitats are insufficiently documented. In many cases, it is deduced that expert judgment is applied, particularly when the characteristics are evaluated qualitatively (e.g. impact of human action). In addition to expert judgement, some of the MSs establish reference values for favourable conditions considering the available literature (e.g. phytosociological categories), catalogues (e.g. lists of characteristic species of the habitat, or of exotic species), or statistical criteria (e.g. percentiles, groupings resulting from multivariate analyses). In general, there is a significant disparity between the different MSs regarding the thresholds or ranges of values for the variables that determine their condition, even within the same habitat.

In addition, there seems to be a considerable variability in the methodologies employed for defining the ranges and thresholds for obtaining condition indicators in forest habitats, since different metrics, methods and calculations are used, resulting in different ranges and thresholds that, in general, are hardly comparable.

However, some variables, such as deadwood, are relatively easy to define, making comparison easier. Even in these cases, different metrics may be used to define the variable. In the case of deadwood, the parameters employed are: (1) volume of deadwood relative to total volume of wood or area (Belgium, Poland - habitat types 9110, 91F0, Spain); (2) number of large size of individuals/logs/specimens per area (ha) (Germany, Hungary, Latvia, Slovakia); (3) percentage of snags relative to stand basal area (Greece); (4) presence/abundance/indices of categories for the stages of decomposition (Denmark, Slovenia). In these cases, in which several MSs use the same parameter, similar thresholds are eventually employed to define the condition of the variable. In fact, it would be worthwhile to compare the thresholds employed for a given forest habitat type in the different MSs in order to converge their values. For example, in the case of deadwood, a threshold of 5 individuals per hectare is used in several methodologies to define a favourable condition, although there are differences regarding the sizes of deadwood.

With other variables, such as characteristic species, ranges and thresholds are highly specific to each habitat type. For example, for habitat type 91E0, in Belgium-Flanders, good condition requires ≥ 7 key species and key species cover, or ≥ 30% proportion of key species; in Ireland, >6 positive indicator species (from a list) are required for assessing good condition; and in Poland, good condition requires a combination of characteristic species of the habitat.

Differences in thresholds determining forest habitat condition naturally exist across biogeographic and socio-environmental gradients, which justifies the use of different values of ranges and thresholds across habitats and regions. However, discrepancies between the MSs regarding the criteria applied to establish thresholds may also be due to specific methodological procedures, and difficult comparisons, even when the monitoring methods are generally comparable. This shortcoming appears even greater since the variables are often defined differently in each country. In addition, some variables are used in only a small number of cases, and there is usually a different procedure for their monitoring, thus impeding comparisons.

2.3 Aggregation methods at the local scale

Local-scale assessment (usually at the level of the monitoring plot, which sometimes are merged with close ones) requires the integration of the measured abiotic and biotic variables using aggregation methods, such as the one-out, all-out rule (minimum aggregation, sensu Langhans et al., 2014), or additive or hierarchical quantitative operations (Langhans et al., 2014).

Therefore, after assessing each variable using a quantitative value, or a qualitative category (indicating, for example, good/favourable, medium/unfavourable, low/bad condition), aggregation is carried out using arithmetic operation (if quantitative values are used) or using aggregation rules, and a weighting can be applied to the individual variables, according to their relevance for the habitat condition, to obtain a more nuanced final assessment. As a result of aggregation, condition categories are applied.

There is a relevant discrepancy among MSs regarding the use of two (good / not good, favourable / unfavourable;) or three categories (favourable / unfavourable-medium/ unfavourable-bad), which difficult comparisons and would require harmonization.

Aggregation methodologies at local scale are reported in most of the MSs, but in 9 of the MSs (including Belgium-Wallonie) information about the aggregation procedure is not available or is insufficiently reported. Seven of the MSs (including Belgium-Flanders) report distinct aggregation procedures for forest habitats, while in 8 of the MSs the procedure is common to all the Annex I habitats.

Some of the aggregation methodologies include **two steps**:

- Step 1 − a set of variables are grouped to obtain partial results for each set. This grouping may be done according to compositional, structural or functional characteristics, but also according to the ability of management to reverse poor condition in the mid or long term. For example, in Germany, Austria and Luxembourg, three groups of variables are established: 1) completeness of the typical habitat structures; 2) completeness of the typical habitat species inventory; 3) impairments. In Belgium-Flanders, the group of variables (or indicators) correspond to: vegetation composition, structure, disturbance and spatial context/coherence, but a weighting is also applied depending on whether they mortgage the favourable condition of the habitat in the long term, thus requiring more than ordinary efforts to remedy it. This allows some degree of nuance in the assessment. For example, in terms of disturbance and habitat structure the site may score favourably, but in terms of vegetation it may score unfavourably.

- Step 2 – the results obtained for the groups of variables considered are aggregated to obtain an overall assessment at the local scale in which the assessment is carried out.

The aggregation procedures operate considering qualitative or quantitative valuations of each variable. These procedures can be grouped in the following categories:

- **Conditional rules**, usually overweighting non-favourable condition, i.e. non-favourable habitat condition is concluded unless all variables are in favourable condition ("one-out, all-out" approach (minimum aggregation, sensu Langhans et al., 2014), or a good condition requires that all the variables that are important for the specific forest habitat type are in good condition. in all the assessed locations. These rules commonly apply different weights to variables. This type of procedure is applied by Belgium-Flanders (see example below), Bulgaria, Cyprus, Denmark, Greece (for compositional variables, such as characteristic species) and Ireland.

Box 3. Example of aggregation at the local scale using conditional rules in Belgium-(Flanders*)*

First, indicators (variables) are considered:

- "Very important": indicators that mortgage the favourable condition of the habitat in the long term, requiring more than ordinary efforts to remedy it
- "Important": indicators whose condition is almost or completely controlled by management.

Next, the following weighting and rules are applied to the various indicators assessed as "important" or "very important":

(1a) at least one "very important" indicator scores unfavourably → unfavourable condition (one-out, all-out rule)

(1b) none of the "very Important" indicators score unfavourably → go to 2:

(2a) half or more of the indicators score unfavourably → unfavourable condition.

(2b) less than half of the indicators score unfavourably → favourable condition.

Source: Article 17 report on the conservation status of the habitat types for the period 2013-2019 (structure and function section).

- **Categorical majority rules**, which establish the habitat condition according to pre-established combinations of ordinal condition categories (i.e. favourable, non-favourable, bad condition). The result of these combinations roughly corresponds to the majority of these categories in the set of variables considered (see example below). In some cases, this average can give different weight to specific variables (Belgium-Flanders). A hierarchical procedure may first apply these rules within variable groups, and then between variable groups. This type of procedure is applied by Belgium-Flanders, Germany, Ireland, Luxembourg and Romania.

Box 4. Example of categorical majority rules in Germany

The measured variables are included in the following three groups:

1) completeness of the typical habitat structures,
2) completeness of the typical habitat species inventory,
3) impairments.

A qualitative assessment of each of these variable groups done using three categories: Excellent, Good and Medium Poor.

Finally, the following rules are applied considering the status of the three variable groups:

- All three variable groups share the same status → common status condition
- Two variable groups share the same status → more common status condition, e.g. 2 Excellent and 1 Good -> Excellent
- However, if there is a C rating, an overall rating of A is not possible, so 2 Excellent and 1 Medium Poor -> Good status
- 1 Excellent, 1 Good and 1 Medium Poor -> Good status condition

- **Quantitative rules**, which apply arithmetic operators or, in specific cases, multivariate analyses, to the values estimated for each variable. These values can be referenced to thresholds (reference values) which describe a favourable condition (France, Spain). Arithmetic operations are then applied. For example, this operation can involve the sum of the differences between the observed value for each variable and the threshold values (France). Given that the metrics applied to the variables are different, the values need to be re-scaled before comparison to reference values and further aggregation. These operations can give different weight to specific variables (e.g. Hungary, Spain – see example below), particularly those related to species composition (Slovakia). In some cases, although the comparison to the reference value can be performed using quantitative values, the output of the comparison is categorical (i.e. favourable condition in Greece and Ireland, unfavourable condition in Hungary), and the aggregation operation corresponds to the number of variables accomplishing the condition output. In the case of Lithuania, a multivariate procedure is used to establish the aggregation of the quantitative variables, and statistical criteria are used to establish the condition status. The result of the final calculation is confronted to thresholds defining habitat condition.

In some cases, a combination of different procedures is applied; i.e. the procedures may vary between types of variables. For example, in Greece, conditional weighted rules are applied for compositional variables, while quantitative (i.e. proportion of favourable indicators) rules are applied for structural variables. Conditional weighted rules are then applied to combine the different types of variables. In Cyprus, a compositional criterion is estimated from the condition status of characteristic species, after aggregating them following a categorical majority rule. This compositional criterion is then combined with a structural criterion following a conditional rule. Finally, Poland reports expert assessment, following undetermined rules.

Box 5. Example of categorical quantitative rules applied in Spain

First, each variable receives a weight according to its relevance.

Second, scores (0,1,2 values) are determined for each variable in each habitat and biogeographical region by three ranges of values

Third, an arithmetic operation is applied to the weighted scores of the different considered variables

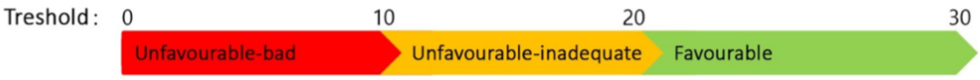
Finally, the condition status is determined by three ranges (corresponding to favourable, unfavourable-undetermined, unfavourable-bad condition) of the result of the arithmetic operation.

Example of weighting, threshold values and scores assigned to each proposed variable for the assessment of 'Structure and function' of habitat type 111MN_11.

Variable	Weighting of the variable	Threshold values for the Alpine region	Score
		≥3	2
$R_{i\ forest}$	1	2	1
		≤1	0
		≥20	2
AB_i	3	[>10-<20]	1
		≤10	0
		≥20	2
$VCC_{i\ dead}$	5	[>5-<20]	1
		≤5	0
		≥6	2
$N\text{-}CD_i$	3	[>2-<6]	1
		≤2	0
		≥4	2
$N\text{-}CA_i$	3	[>2-<4]	1
		≤2	0

$$ECL = R_{i\ forest} + (3 * AB_i) + (5 * VCC_{i\ dead}) + (3 * N\text{-}CD_i) + (3 * N\text{-}CA_i)$$

Range ECL = 0 – 30



Ri forest: Tree species richness; ABi: Basal area; VCCi dead: dead wood volume; N-CDi : Number of diameter classes; N-CAi: Number of height classes)

Source: Pescador et al. 2019a

Once the condition has been assessed at local level using the abovementioned procedures, it can be scaled-up on a larger scale, as the biogeographic region, by aggregation as described in the next section.

2.4 Aggregation at biogeographical scale

Overall, most MSs follow the recommendations provided in the Article 17 reporting guidelines for the period 2013-2018, which establish that "if 90% of the habitat type area is considered as in 'good' condition, then the status of the 'structure and functions' parameter is 'favourable'. If more than 25% of the habitat area is reported as 'not in good condition', then the 'structure and functions' parameter is 'unfavourable-bad'". However, some MSs have used different methods for aggregating the assessment of local forest condition in order to obtain an overall assessment at the biogeographical scale.

Some MSs use indexes and descriptive statistics for aggregation at the large spatial scale. In Lithuania, for example, the decision on habitat condition at the national level is made using a multivariate approach, statistically evaluating the values of all parameter indicators by using non-hierarchical cluster analysis methods, such as K-means (a common data matrix procedure based on the indicator values of each surveyed site), and then allocating them to groups and assigning these groups to conservation condition classes. Ordinal analysis techniques, such as Principal Component Analysis (PCA), are used to visualise and evaluate the relationships between groups.

Finally, a number of MSs either do not provide information on aggregation methods or state that they are working on them, but that they are not yet ready for use.

2.5 Selection of localities

Some MSs focus habitats monitoring only or mainly in Natura 2000 (e.g. Cyprus, France, Poland, Hungary). Among those who carry out the habitats monitoring both inside and outside Natura 2000 sites, three main ways of selecting the localities for monitoring forest habitats are used: (1) expert judgement; (2) random or regular stratified sampling; (3) permanent plots on the National Forest Inventories grid.

1) **Expert judgement**: localities or stations to perform monitoring of forest habitats are selected by one or various experts with the aim of reflecting the geographical extent and variation within the individual habitat types. The minimum habitat area to be selected as a monitoring station is not always specified, but some MSs propose 5 ha. Once the localities are selected, monitoring plots are established by either using again expert judgement or by using a reference grid. The size of the cells of the reference grid varies between MSs or forest habitats (10 m, 50 m, 100 m). In some other MSs, size is not specified. Most of the MSs select monitoring plots randomly within the grid. The number of sampling plots must be representative of the variability within the habitat and proportional to its total surface and its geographical diversity, considering regional peculiarities. The minimum number of samplings varies between MSs, but it is sometimes not specified. Some MSs explain that it should be one every 2 ha, with at least one sampling per homogeneous surface unit.
2) **Regular or random stratified sampling**: localities or stations to perform monitoring are selected using a GIS and forest maps and a grid to determine random sampling plots. The dimensions of the grid cells are adjusted to the size of the smallest units (polygons). For example, in some cases a grid of 10x10 km is used for selecting monitoring localities for all forest habitats except for those that are underrepresented, whose localities will be selected using a 5 km reference grid. Other MSs opt to use a 4x4 km grid network. Monitoring localities within the grid are then selected by gathering a concrete number of sampling plots per forest habitat type. Accordingly, some MSs propose 150 monitoring

plots while others establish a minimum of 40 sampling plots per forest habitat type (see also point 2.6). The distance between monitoring plots depends on the size of the grid.

3) **Permanent monitoring plots**: seven MSs use permanent plots for forest habitat monitoring. Six of them make use of the inventory plots already established by their corresponding National Forest Inventory (NFI). The only MS not using NFI plots to monitor forest habitats uses its own system of national permanent plots for the assessment and monitoring of forest habitat types. Both approaches have the advantage of optimising efforts and resources (Pescador et al., 2022). However, not all the NFI of the MSs use the same methodology for selecting localities or the same monitoring protocols.

2.6 General monitoring and sampling methods

Previous works have already reported standardised protocols for monitoring and sampling of habitat types (Lengyel et al., 2008; Ellwanger et al., 2018). However, forest monitoring procedures collected from MSs are not harmonised and they differ in both sampling protocols and monitoring frequency. The main particularities are described below.

2.6.1 Sampling protocols

- **Shape of sampling plots:** Only a few of the methodologies analysed provide information regarding the shape of the sampling plots and, in fact, use different types. For example, some MSs use circular sampling plots while others use square, rectangular or transect plots.
- **Size of sampling plots**: The area of the habitat polygon selected for monitoring also differs between MSs. Some provide a minimum and a maximum surface (e.g., between 1 and 5 ha), while others establish a unique plot size (0.1 ha, 32x32 m, 20x20 m).
- **Number of plots**: Few MSs provide the exact number of plots per habitat type to be surveyed. Some MSs provide instructions for calculating this number using a statistical approach. The aim is to know the minimum number of plots that need to be surveyed in order to statistically test whether the proportion of locations with an unfavourable habitat quality differs from 25% (the EU threshold value) and to have a certain confidence interval (minimum detectable difference) regarding that number. Therefore, the relationship between sample size and the minimal detectable difference for a given significance level α and a power π (Manly & Navarro, 2014) must be analysed. The significance (α) is the probability of a Type I error, i.e., the probability of concluding that there is an effect based on a sample, when there is no effect in the habitat occurrences. The power (π) indicates the probability of detecting an effect based on a sample, when the effect also exists in reality (Type II error). Since reduction in the probability of committing a Type II error increases the risk of committing a Type I error (and vice versa) a delicate balance should be established between the minimum allowed levels for Type I and Type II errors. The ideal power of a study is 0.8 (which can also be specified as 80%). Sufficient sample size should be maintained to obtain a Type I error (α) as low as 0.05 or 0.01 and a power as high as 0.8 or 0.9. However, not all forest habitats present enough surface within the MSs. Furthermore, not all MSs have the same resources for fieldwork. Thus, a compromise between minimum sample size and reliability and accuracy should be accomplished (see Table 5).

Table 5. Examples of minimum sample size calculations with a power of 0.8 using different margins error.

Country and reference	Type I error (α)	Minimum sample units
Spain (Pescador et al., 2019a)	0.15	40
Belgium-Flanders (Westra et al., 2022)	0.05	384

- **Monitoring methodology**: All MSs use fieldwork for the monitoring. Some use Braun-Blanquet relevés, applying the phytosociological method, and six MSs take advantage of the permanent plots of their respective National Forest Inventories (see section 2.5). Only one MS also considers using new technologies, such as LiDAR, for monitoring purposes (Vayreda et al., 2019).

2.6.2 Monitoring frequency and sampling period

- **Sampling period**. Most fieldwork is performed during spring or summer. There are differences between the MSs with regard to the date (season, month chosen), though this cannot be considered relevant.
- **Monitoring frequency**. Most countries use the monitoring frequency requested by Art.17 of the Habitats Directive, i.e., six years. Some states apply a longer period (12 years) to complete a monitoring cycle for each plot. Therefore, they use a larger number of monitoring plots, and plots are visited twice or even three times during the monitoring cycle. Consequently, not all monitoring plots are visited for the six-year reports.

2.7 Other relevant methodologies

Currently, there are several protocols and systems in place for monitoring the conservation status of forest habitats worldwide. Some of these may complement those used by the EU MSs, e.g., with regard to the selection of indicators, setting threshold values, aggregation methods, by the use of new technologies such as remote sensing, modelling, etc. These protocols vary by region and are often part of broader environmental and conservation frameworks. While many countries have established forest monitoring protocols, only a few have performed forest condition assessments.

2.7.1 Forest monitoring protocols from other countries and regions

One of the most recognised procedures is the **Smithsonian Institution/Man and the Biosphere (SI/MAB) protocol for forest monitoring**, which belongs to the Monitoring and Assessment of Biodiversity programme. The main objectives of the forest monitoring component of the SI/MAB programme (Dallmeier, 1998) are to: (i) track changes in forest cover by monitoring deforestation and reforestation rates; (ii) assess forest health and biodiversity by tracking species diversity, abundance, and ecosystem processes; (iii) understand human impact by investigating the effects of human activities such as logging, agriculture and urbanisation on forest ecosystems; and (iv) support conservation and sustainable management by providing data to inform conservation strategies and sustainable management practices. The methodology proposes different techniques:

1. **Remote Sensing and Satellite Imagery**: Using satellite imagery from sources such as Landsat, Sentinel and MODIS to monitor changes in forest cover and land use. It employs remote sensing technologies to detect and analyse deforestation, forest degradation and changes in vegetation density.
2. **Field Surveys and Ground-Truthing**: Conducting systematic field surveys to collect data on tree species composition, forest structure and health indicators. It employs ground-truthing satellite data with on-the-ground observations to validate and improve the accuracy of remote sensing analyses.
3. **Long-Term Ecological Research (LTER)**: Establishing long-term ecological research plots within biosphere reserves to monitor ecological processes, species dynamics and forest growth patterns over extended periods. It measures parameters such as tree growth rates, soil health, carbon sequestration and biodiversity indices.
4. **Geographic Information Systems (GIS)**: Using GIS to integrate and analyse spatial data on forest cover, land use, biodiversity and human activities. It creates detailed maps and visualisations to track changes and identify critical areas for conservation.

The SI/MAB protocol is mostly used in tropical forest systems. Thus, countries in **Latin America, such as Bolivia, Brazil, Ecuador, Guatemala, Panama and Peru**, have been notably involved in the programme, using the model to enhance their forest monitoring capabilities. In addition, **Canada** adapted the protocol for use in temperate forests and published forest monitoring protocols in Canada's Ecological Monitoring and Assessment Network (EMAN), established in 1994 (Roberts-Pichette and Gillespie, 1999).

Nowadays, however, most of Canada's forests are monitored by the **Canadian National Forest Inventory** (Gillis, 2001). In 2000, Canada designed a new National Forest Inventory[1] with a statistically valid sampling approach, a consistent methodology and a network of plots to provide the framework for ongoing re-measurement and monitoring. The NFI's design-based statistical survey of permanent, geo-referenced plots that sample all of Canada's forests was established over a seven-year period, from 2000 to 2006. Canada is currently engaged in the second re-measurement.

As in Canada, forest monitoring is implemented in several countries by their **National Forest Inventories (NFIs).** The first National Forest Inventory was conducted in Norway in 1919. This pioneering effort aimed to systematically assess the forest resources of the entire country, setting a precedent for future forest inventories globally. The Norwegian inventory collected comprehensive data on forest composition, volume, growth and health, establishing methodologies that influenced forest management practices and policies in other countries[2]. Each of the 22,000 permanent plots is re-measured regularly according to a five-year rotation. This means that one-fifth of the plots are measured per year and it takes five years to collect data from all plots. The entire country is, however, included in each year's selection of plots, making it possible to obtain updated forest statistics for the entire country on a yearly basis.

However, just a few countries have taken a further step and use their NFI programmes to assess forest ecological condition. One of these is the **United Kingdom**, whose Forest Research Agency assessed **woodland ecological condition in Britain** by using the NFI-recorded ecological data (NFI survey cycle 2010-2015). Fifteen woodland ecological condition indicators (WEC indicators) were assessed at each woodland stand surveyed. In turn, the data

[1] https://nfi.nfis.org/en/history
[2] https://www.nibio.no/en/subjects/forest/national-forest-inventory

for the 15 WEC indicators were compared to a series of 15 benchmarks representative of an ancient semi-natural woodland (ASNW) in good condition, enabling a score of condition to be calculated. This score was used to classify stands according to their ecological condition: favourable, intermediate or unfavourable[3].

Regarding the UK, it is also worth mentioning the initiative led by the NGO **Woodland Trust**[4], which in 2021 published the report "**State of the UK's Woods and Trees**" (Reid et al., 2021), which gathers disparate sources of data on woods and trees.

Another example is the **State of Victoria in Australia**. The **Victorian Forest Monitoring Program (VFMP)**[5] is focused on assessing the extent, state and sustainable development of Victoria's forests. It involves collecting data to detect long-term trends and predict future changes, thereby informing effective land management policies and decisions. The Program uses a network of 786 permanent ground plots which are stratified or grouped into 21 distinct regions according to Victoria's 11 bioregions. These plots are analysed for forest structure, species diversity, canopy condition and soil characteristics. The data helps in addressing issues like fire and flood impacts, habitat protection, carbon accounting and forest health. In addition, the **State of the Forest report**[6] is published every 5 years, for which 52 indicators are used, grouped into 7 criteria: 1) Conservation of biological diversity; 2) Maintenance of productive capacity of forest ecosystems; 3) Maintenance of ecosystem health and vitality; 4) Conservation and maintenance of soil and water resources; 5) Maintenance of forest contribution to global carbon cycles; 6) Maintenance and enhancement of long-term multiple socio-economic benefits to meet the needs of societies; and 7) Legal, institutional and economic framework for forest conservation and sustainable management. Indicators are assessed according to their ecological condition: Good, Fair, Poor and Unknown.

Finally, in the **USA**, there are two programmes related to forest monitoring that have been integrated since 1999. The **Forest Inventory and Analysis (FIA)** programme of the US Forest Service[7] has been monitoring and reporting on status, condition and trends in the nation's forests since 1928. Both urban and non-urban forests are included in the programme. The latter are studied by the Nationwide Forest Inventory (NFI), a network of permanent plots located in non-urban areas that are forested (or capable of being forested). NFI plots are re-measured every 5-10 years depending on location. Information on the site, land use and trees (both standing and dead) is collected on all plots. Additionally, information about downed woody material, soils and understory vegetation is collected on a subset of plots. Urban forests are studied through the Urban Inventory, an inventory programme that monitors the country's urban forests, examines the social dimensions of urban forests and green spaces, and estimates the industrial and non-industrial uses of urban wood. Recently, the **Forest Health Monitoring (FHM) programme**[8] has been integrated into the FIA (Smith, 2002). This is a national programme designed to determine the status, trends and future forest conditions using an indicator-based approach on an annual basis. The FHM programme integrates data from ground and aerial surveys, risk assessments, remote sensing and other sources to

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[3] NFI Woodland Ecological Condition Scoring Methodology and indicator scores are available to download at https://www.forestresearch.gov.uk/tools-and-resources/national-forest-inventory/what-our-woodlands-and-tree-cover-outside-woodlands-are-like-today-nfi-inventory-reports-and-woodland-map-reports/nfi-woodland-ecological-condition/.

[4] https://www.woodlandtrust.org.uk/state-of-uk-woods-and-trees/.

[5] https://www.forestsandreserves.vic.gov.au/forest-management/victorian-forest-monitoring-program.

[6] https://www.ces.vic.gov.au/publications-library/state-forests-2018-report.

[7] https://www.fs.usda.gov/research/programs/fia.

[8] https://www.fs.usda.gov/science-technology/forest-health-protection/monitoring.

assess forest health issues that affect the sustainability of forest ecosystems. FHM assesses conditions on all forest land through a partnership involving the USDA Forest Service, State Foresters, other state and federal agencies, Tribal Nations, non-governmental organisations and academic groups. Local data are aggregated to a larger geographic level, namely, "mega-regions".

As a final point, the use of new technologies is essential for forest monitoring in countries with large extensions of tropical forest where fieldwork is unfeasible. One example is the **Amazon Monitoring Program: PRODES**[9] and **DETER**[10] **projects** in **Brazil**. Both are run by the National Institute for Space Research (INPE) with the goal of monitoring and controlling deforestation, degradation, fires and other impacts on the tropical forest and other biomes. Satellite imagery is used to generate annual deforestation rates as well as daily alerts.

At European level, Maes et al. (2023) carried out a **spatial assessment of the condition of forest ecosystems in Europe** following a United Nations global statistical standard on ecosystem accounting (SEEA-EA). They measured forest condition on a scale from 0 to 1, where 0 represents a degraded ecosystem and 1 represents a reference condition based on primary or protected forests. The assessment showed that the condition across 44 forest types averaged 0.566 in 2000 and increased to 0.585 in 2018. Forest productivity and connectivity were comparable to levels observed in undisturbed or least disturbed forests. One third of the forest area was subject to declining condition, signalled by a reduction in soil organic carbon, tree cover density and species richness of threatened birds.

In a study on **mapping forest condition in Europe**, Marín et. al. (2021) al. present a methodological framework for developing and operationalizing a high-resolution (1 km) forest condition indicator at a European scale, designed to support forest biodiversity assessments and sustainable forest management initiatives. The methodology integrates structural, functional, and compositional aspects of forests into a single indicator, utilizing harmonized, open datasets to provide spatially explicit information on forest health and vitality.

2.8 Conclusions

Forests habitats cover around one third of Europe's land area and occupy a wide biogeographical range in the European territory. However, they share some **common fundamental characteristics**, regarding their structural and functional features, which are determined by the arboreal nature of their dominant species. In general, MSs use variables that characterise forest habitats appropriately and that can be framed within the SEEA Ecosystem Condition Typology (ECT). The inclusion of some variables in this typology is, however, not always unambiguous, such as those related to old trees and deadwood, which share attributes of structural and functional variables.

Therefore, there is an appreciable consensus among MSs about the main groups of characteristics and variables that are useful to assess forest condition, which fundamentally correspond to the **characteristics of composition and structure**. On the other hand, there are some variables of great importance in the functioning of forests that are poorly valued for determining forest habitat condition. Such is the case with soil characteristics − although they are sometimes evaluated indirectly through a broad description of habitat quality – which are essential components in forest habitats owing to their key role in nutrient recycling and water

[9] http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes
[10] http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/deter/deter

uptake. In addition, the use of variables that describe forest functioning and dynamics (e.g., successional stage), is undervalued and lacks homogeneity. In general, the vision of the conservation status of forests is too static. For example, the positive or negative implications of the disturbance regime or biotic interactions are rarely valued. It is also notable that variables closely related to the state of forests, such as the state of health (decay) of the forest canopy, or the presence of animal species or microhabitats, are not commonly used.

Overall, the **general monitoring methodologies** (mainly based on field surveys and often using forest inventory networks, expert judgement and GIS analysis) used to determine habitat condition are common to the vast majority of MSs, regardless of the biogeographical region in which they are located. However, each MS applies its own procedures and protocols, thus hindering comparisons and the identification of general patterns.

Despite the fundamental similarities between the different forest habitats, some present their own abiotic, compositional, structural and functional characteristics. With regard to abiotic characteristics, **riparian forests** are highly determined by the water regime, while **bog woodlands** are influenced by superficial water table levels that determine the composition of accompanying species (bryophytes and lichens) and processes associated with flooded soils, and **dune forests** are determined by their sandy substrate close to the sea.

The variables that generally have the most weight for assessing the conservation status of forest habitats are those corresponding to the **characteristic and typical species**, the presence/abundance of **deadwood and the vertical structure** (layers) of the forest. Furthermore, it is common to consider variables that describe the **impact of human activity**, or the degree of conservation/impairment, which are associated with pressures, when assessing habitat condition. However, the inclusion of variables describing human action or non-human disturbances for habitat condition assessment may produce artefacts by assuming that these actions necessarily reduce habitat condition. Appropriate rationales regarding the relevance of such disturbances should be considered when applying aggregation criteria for these variables in order to establish habitat condition.

At the forest habitat level, while the number of used variables can be considered large enough in most cases, some habitats (e.g., 91S0, only found in Bulgaria; 91V0, 91X0 and 91Y0, only found in Romania; 9280, 9290 and 9310, only found in Greece) are assessed with a low number, which corresponds mainly to compositional variables that measure characteristic or typical species. In these cases, the assessment of habitat condition relies on a too restricted number of variables. In fact, many of the MSs only use around half of the identified subgroups of relevant variables (Table 4). Nevertheless, a **large number of specific variables** are used by different MSs. In many cases, these variables are very similar in their foundation, though the name and metrics commonly differ. Based on the wide variety of methodologies employed, we have identified more than 500 different variables or metrics used to assess forest habitats in the consulted methodologies. While recognising that some habitats need specific variables depending on their particular characteristics, the variety of methodologies generally results in a significant overlap between variables describing similar characteristics. In fact, there is greater harmonisation in the methodologies used to characterise the different habitats within the same MS than in a given habitat across different regions encompassing several MSs.

Differences in **setting thresholds** to determine the condition for the same variables is due to biogeographical and ecological differences across habitats in the European territory, but also to the different methodological approaches and metrics applied. For example, vegetation relevés (which sometimes follow the phytocenological method) are frequently used to identify characteristic herb species, but the resulting habitat condition may differ, depending on the metrics used for measuring the corresponding variable. There is also a significant heterogeneity or limited consistency between MSs regarding the terminology used, insufficient information on describing the variables and metrics, and on the rationale for their use. It is understandable and desirable that different habitats can have specific thresholds that define the conservation condition for the particular variables that characterise them, but it is not recommended to have large differences in the evaluation procedures for the same habitat, among different MSs.

The Member States use different **aggregation methods** for the variables used to determine the condition of the habitat at the local scale. Moreover, in a significant number of methodologies, these procedures are not sufficiently detailed, or even developed. Where these methods are sufficiently described, they exhibit notable differences, from the application of strict conditional rules, to those based on the majority of defined categories or more quantitative methods. In many cases, these methodologies are common to terrestrial habitats other than forest habitats. To establish reference values of favourable conditions (Jakobsson et al., 2020), expert judgement is frequently applied, or inferences are made from the literature, though sometimes statistical criteria are applied (Kovac et al., 2016). In any case, it should be noted that there are important gaps in information about the criteria for establishing the threshold values that determine the favourable condition of habitats.

There is a certain **consensus on the procedures for aggregating variables at the supra-local level**, largely because the European Commission guidelines provide quantitative criteria. These criteria however have not always been strictly applied by all MSs and there were some disparities in the past regarding the percentage of surface area or monitored localities that should be in a given condition to conclude the result of the assessment at the regional level.

The **monitoring** procedures for collecting the information that determines forest habitat condition are largely based on periodic field observations (every 6-12 years). In most countries, instructions are provided for carrying out the sampling, though this information is not available in approximately one-third of the methodologies analysed. Only a small number of MSs take advantage of the permanent plots of their respective National Forest Inventories (NFI) (Alberdi et al., 2019, Heym et al., 2021). Other MSs use specific field surveys, following different protocols for the selection of the localities.

Some MSs use expert judgement for **selecting monitoring locations** that should reflect the geographical extent and variation in each habitat type. In other MSs, regular or random stratified sampling is applied using gridded forest maps generated and Geographical Information Systems. The monitoring focus on Natura 2000 sites and protected areas in some MSs. The minimum number of monitoring plots is calculated using different algorithms, taking into consideration that this number must be related to the total habitat surface in the MS. Most MSs agree on the convenience of using a specific number of plots for each forest habitat.

Monitoring protocols and the sampling methodology differ in terms of the shape and size of the sampling plots. Usually quantitative data on composition and structure collects, although in some cases phytocenological methodologies are used. The use of new technologies, such as **remote sensing**, is not widespread and serve more as a tool for selecting plots or analysing landscape features than for diagnosing structure and function.

3. Guidance for the harmonisation of methodologies for assessment and monitoring of habitat condition

3.1 Selection of condition variables, metrics and measurement methods

As above mentioned there are both similarities and differences in the variables, metrics and measurement methods used by the different MSs to assess the condition of forest habitats, which hampers the attainment of comparable assessments across MSs, and their aggregation at EU level.

To harmonise the selection of forest condition variables, some **general principles** should be adopted:

- Any given habitat is defined by a set of characteristics, irrespective of its location in different MSs; these characteristics are translated to a set of measurable variables.
- The forest variable needs to be clearly related to forest condition (directionality principle) and must be sensitive to natural threats or human pressures that decrease favourable condition (Maes et al., 2023).
- There are contextual factors operating in the different MSs, which may determine the values of the variables that characterise the habitat condition as favourable. These factors include biogeographical gradients, historical, cultural and socio-economic background.
- For a given habitat, the final assessment of habitat condition, based on variables that characterise the habitat, should be equivalent for the different MSs, after accounting for the contextual factors of each MS.
- Other contextual variables linked to local environmental conditions (e.g., temperature, topography, soil types, hydrological conditions) can also be useful for sampling design, setting thresholds and understanding changes in habitat condition.

In addition, harmonisation of the selection of variables must consider a set of **common requirements**:

- For any forest habitat, all the main types of characteristics, according to the SEEA EA typology (abiotic physical and chemical, biotic compositional, structural and functional, landscape variables), must be measured in each MS. Among the corresponding variables, a set of common essential condition variables should be necessarily measured in each MS, following equivalent procedures, and must result in common metrics. In addition, a set of recommended condition variables may be applied in some cases, considering contextual factors influencing the habitats in the different MSs. Finally, specific condition variables should be measured in certain habitats (e.g., riparian forests) or in particular situations.
- All common essential condition variables describe fundamental characteristics of forest habitats, reflecting their ecological quality or integrity.
- The number of common essential condition variables should be the minimum needed to determine habitat condition, avoiding redundancies, (following the parsimony criterion, Czúcz et al., 2021), according to the main characteristics of forest habitats.
- The common essential condition variables should accomplish the criteria of intrinsic and instrumental relevance, validity, reliability, availability, simplicity and compatibility (Czúcz et al., 2021).
- The extent to which the essential variables are relevant for a given habitat type in each MS can be adjusted when setting thresholds.

- The variables should be suitable for regular measurement at appropriate spatial scales over prolonged periods in order to track changes in habitat condition (Maes et al., 2023).
- The description of the condition variables, metrics and measurement procedures applied by each MS must be reported and perfectly understandable so that they can be applied in other MSs.
- Common training on how to measure the condition variables should be programmed for experts from the different MSs in order to achieve full harmonisation.

A proposed list of **essential, recommended and specific condition variables** for forest habitats is shown in Table 6, including metrics and general measurement procedures. Essential variables correspond to characteristics that describes the common essence of forests (e.g., tree species richness, canopy cover), the distinctness of the habitat (e.g. characteristic species) or their condition (e.g., typical and alien species, canopy health, coarse woody debris, human-induced impact). Recommended variables correspond to common variables that are relevant but that can fail to be measured in some contexts (particular habitats, regions). Specific variables correspond to variables that should be measured in some particular habitats.

The proposed list of variables is based on the main features of forest habitats as described in section 1.2.1, on the information provided by MSs regarding the assessment of forest habitat condition, and on specific literature on forest habitat condition (Alberdi et al., 2019; Bastrup-Birk et al., 2014; Burrascano et al., 2013; Cantarello & Newton 2008; Czúcz et al., 2021; Del Barrio et al., 2019; Kovac et al., 2016; Maes et al., 2023; Pescador et al., 2109a; Pescador et al., 2022).

The proposed metrics are intended to be easily, but reliably obtained, most of them at plot level. Given the relatively slow dynamics of forests, most of these variables are not required to be measured yearly, with the exception of those related with groundwater, canopy cover and health, and browsing.

The main **abiotic** variables refer to **soils**, which in forest habitats are key for nutrient recycling and plant uptake. Thus, **litter depth**, though spatially heterogeneous, is considered as an essential abiotic physical variable roughly estimating soil capability to provide such functionality. In turn, estimating the absence of soil losses (estimated from **bare soil**) provides information of soil preservation and is also considered an essential variable. These variables should be assessed according to the specifities of habitats and topography since it may scarcely be discriminant in some forest habitats (e.g. in boreal regions). **Litter cover** is also associated with soil conservation and is also included as a specific variable, since its importance largely varies between forest habitats, depending on phenology and decomposition rates (i.e., variability between deciduous and evergreen forests, or between boreal and Mediterranean forests). **Soil organic matter** is also closely related to carbon cycle and stocks, as well as nutrient recycling and availability, in addition to host soil biodiversity, and is proposed as an essential abiotic chemical variable; it is often used as an indicator of soil health and quality. **Acidity**, estimated from **soil pH**, in forests can indicate and influence soil health, nutrient availability and microbial activity and is also proposed as an essential variable. **Soil nutrient content**, especially Nitrogen and Phosphorous, is also crucial in forest functioning, but the difficulties to establish large-scale analyses for the different habitats lead to propose them as recommended, considering baseline level specific of habitats and regions. **Groundwater level** is included as a specific variable, according to the particularities of some forest habitats (e.g., 9150 calcicolous beech forests, 91D0 bog woodlands). Finally, **forest continuity** is proposed as a specific measure of landscape characteristics for riparian forests

(Bastrup-Birk et al. 2014) (see also section 6. Guidelines to assess fragmentation at appropriate scales).

The essential proposed variables describing biotic **compositional** characteristics are characteristic species, animal species, tree richness and alien species. **Characteristic species** (mostly vascular plants, but also bryophytes and lichens in some habitats) are essential descriptors of forest habitats and should be based on a pre-established list of species for each habitat. Typical species are also considered in the assessment of the habitat structure, but their status should be assessed separately and the result of their assessment should then be integrated in the overall assessment resulting from the aggregation of the other condition variables. Typical species usually indicate favourable condition and may be selected from a variety of taxonomic groups, including vascular plants, bryophytes, lichens, fungi, mammals (including bats), birds, amphibians and some invertebrates, with particular focus on pollinators (see also section 1.3 in this document). The assessment of the typical species status will need to be addressed at wider scale, across the habitat.

Animal species are relevant indicators of forest habitats. Forest birds in particular are key biodiversity indicators and should be recorded. Threatened forest birds and specialized species like woodpeckers, which are sensitive to habitat quality and old-growth conditions, are particularly valuable. Other animal species that depend on forest habitats could be also considered, including some mammal species (e.g., forest bats, squirrels, martens, etc.), amphibians (salamanders, toads) and insects, especially beetles (Coleoptera). Some birds and rodents also play a crucial role in forest species dispersion. The most relevant species for each habitat type and region should be identified and recorded, as appropriate.

Tree richness is considered an essential variable since it reflects biodiversity value in mixtures of tree species in many European forests, that have historically been impoverished, though it may be much less relevant in boreal and alpine forests. This variable excludes alien, introduced and harmful species to avoid inflation of values by species that indicate poor condition. **Alien species** is also proposed as an essential indication of poor condition, since these species are considered one of the main drivers of the biodiversity crisis, owing to their negative impact on native populations and their potential to disrupt ecosystem functioning (Keller et al., 2011). Other relevant variables are **shrub richness**, with a significance analogous to tree richness, and **harmful species**, which determine poor condition. Both variables may exhibit differences between habitats with regard to their relevance and are proposed as specific.

The essential proposed variables describing biotic **structural** characteristics are **canopy cover**, vertical stratification, large living trees and coarse woody debris. The canopy layer is the basic feature of forests habitats and denotes their continuity at stand level. **Vertical stratification** (layers) reflects the structural diversity of the habitat and is strongly related to the existence of non-coetaneous layers of trees. **Large living trees** provide a simple estimation of forest age and habitat persistence over time, and is closely linked to forest maturity; this variable is widely recognised as indicator of old-growth forests (Burrascano et al., 2013, Bastrup-Birk et al., 2014). Similarly, **deadwood** (both standing and lying) is considered a key indicator of old, mature forests and provides microhabitat for biodiversity (Burrascano et al. 2013, Sandstrom et al 2018). Given the variety of available metrics, the categorical proposal aims to facilitate simple, reliable and comparable estimations, though the recognition of related standing logs is advisable. Recommended variables include **basal area, canopy height** - which also constitute a basic characteristic of forests -, uneven structure, roughly related to vertical stratification, but focused on trees, thus informing about their demographic dynamics and legacy (i.e. non-coetaneous forests); and **microhabitat** occurrence, a key forest characteristic, which can be considered an indicator of animal biodiversity (Larrieu et al., 2018). These variables are only proposed as recommended because their estimation involves great survey effort. Finally, **gaps occurrence** is proposed as specific, depending on the context of the forest habitats in the different MSs. Note that high values of this variable may inform about a poor condition of the habitat due to disturbances or human impact, while low values may challenge stand dynamics and regeneration of trees. Our proposal mostly relies on vegetation-based structural variables; however, microhabitat occurrence is also associated with animal biodiversity, which is explicitly addresses in compositional characteristics (e.g. typical species).

Among the proposed essential variables describing biotic **functional** characteristics, **canopy health** (estimated by visually integrating defoliation level and the existence of other symptoms) is proposed as essential variable broadly describing the impact of abiotic (e.g. drought, frost) and biotic stressors (e.g. pests and pathogens) and disturbances over a baseline of regular condition, and it is widely used in long-term monitoring of forests. **Canopy greenness** is often used as a proxy of forest productivity at large spatial scales by using remote sensing-derived indexes (NDVI, NDWI, EVI) (Maes et al., 2023). However, the saturation of this signal, their seasonal fluctuations and the need to be calibrated with field empirical estimations of forest productivity for specific habitats and sites does not support its inclusion as an essential variable, though we recommend it whatever available and suitable.

The **regeneration** of characteristic or typical tree species is also proposed as an essential variable since it informs about the dynamics of engineering species of the habitat and its permanence over time. In general, this variable is underrepresented in MSs assessments and its consideration should be reinforced, at least by employing categorical metrics. Also, a succinct description of the **successional stages** at site level is informative about habitat dynamics and is proposed as specific variable, since the successional typification may not always be feasible for some forest habitats. Note that a forest habitat in good condition may contain different stages of successional development, accounting for the natural dynamics of forests (Perry 2008), from pioneer stages (e.g. gaps due to natural causes) to areas with mature or even senescent forest. This assessment scales-up from plot level to larger spatial scales.

Browsing is proposed since it roughly informs about the state of the forest trophic chain, although its value as a condition indicator is expected to exhibit a humped pattern (i.e. heavy herbivory is likely to negatively impact forest condition, while low to moderate browsing indicates a richer trophic web, even favouring regeneration and reducing plant competence). Browsing is proposed as specific variable, since it may be largely dependent on biogeographical and land use contexts. Carbon assimilation and stocks are important forest functions with relevance at regional and global scales (e.g., for restoration goals), but they are not considered here as determinants of habitat condition, though several of the proposed variables can be used for its accounting.

Human-induced impact is often related to the disruption of forest functioning by human impacts, disturbances, and biotic and abiotic stress and is considered as an essential variable. Related metrics are not very commonly considered in the current assessments by MSs, though they are clearly related to ecological condition, are widely recognized as key indicators in the literature (Bastrup-Birk et al., 2014, Kovac et al., 2016), and are often related to naturalness (Maes et al., 2023). While it is not recommended to use pressures to assess habitat condition, the effects of some pressures can be a good indicator of condition, e.g., canopy loss, which is a widely recognised indicator of forest health. **Non-human disturbances** are also considered as essential variable to be measured in relation to the expected natural disturbance regime according to the particularities of the habitats and regions.

Two essential variables are proposed for **landscape** characteristics: **habitat patch size** and **fragmentation**. They are basic descriptors of this type of characteristics in forests, that can be effectively estimated from remote sensing sources. The proposed metrics represents a small fraction of the used metrics for these variables and can be accommodated to the metrics used in the assessment of habitat condition at large spatial scales. In addition, the continuity of riparian vegetation in terms of length and width is proposed as a specific variable for forest riparian forests.

In addition to the proposed condition variables, it seems advisable to measure other **contextual variables** associated with environmental characteristics (e.g. climate, topography, lithology) that can influence the habitat condition, are useful to define thresholds for the condition variables and to interpret the results of the assessment, but which are not integrated into the aggregation of variables to determine the habitat condition. The information for these contextual variables can be obtained from existing data sources, e.g. meteorological stations can provide information on temperatures and precipitation, data on topography and lithology can be obtained from maps, etc. These variables are not directly used to determine the condition of the habitat but can be very useful and necessary also in the context of climate change and should therefore be integrated in the habitat monitoring at the appropriate scale.

Table 6 provides a summary overview of the proposed condition variables for assessment and monitoring of forest habitats, including their metrics and measurement procedures.

9150 Medio-European limestone beech forests of the *Cephalanthero-Fagion*
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Table 7. Proposal for condition variables for forest habitats, including metrics and measurement procedures

Variables	Metrics & measurement units	Measurement procedures	Application	Considerations relating to methodologies
1. Abiotic characteristics				
1.1 Physical state characteristics				
Groundwater level	kPa	Piezometers	Specific	Likely to be seasonally measured.
Bare soil	%	Visual estimate of % cover - Plot survey	Essential	Distinguish rockiness and erosion.
Litter cover	Cover (%)	Visual estimate of % cover - Plot survey	Specific	
Litter depth	cm	Measured in Plot survey	Essential	
1.2 Chemical state characteristics				
Soil organic matter	Percentage (%), or grams per kilogram (g/kg) of soil	Analysis of plot samples	Essential	
Acidity	pH	Analysis of plot samples	Essential	
Nutrient content	N, P concentration	Analysis of plot samples	Recommended	
2. Biotic characteristics				
2.1 Compositional characteristics				
Characteristic plant species	(1) number (% of total), (2) cover (%)[1] of characteristic species from a reference list	Identification and cover estimate - Plot survey	Essential	Establish list of characteristic species (mainly vascular plants, but also bryophytes and lichens in some habitats) according to specific habitat and region.
Animal species	Presence, number	Identification of presence, signs and traces of animal species- Plot survey	Essential	Establish list of characteristic animal species for each habitat and region, including birds, mammals (incl. bats), amphibians and some invertebrates.
Tree species richness	number of species ha^{-1}	Plot/Site survey	Essential	Sampling-size dependent; exclude alien and harmful species.

Variables	Metrics & measurement units	Measurement procedures	Application	Considerations relating to methodologies
Shrub species richness	number of species ha^{-1}	Plot/Site survey	Specific	Sampling-size dependent; exclude alien and harmful species.
Alien species	(1) number of species ha^{-1}, (2) total cover (%)[1]	Plot survey	Positive	Sampling-size dependent. Likely to be yearly monitored.
Harmful species	(1) number of species m^{-2}, (2) cover (%)[1]	Plot survey	Recommended	Sampling-size dependent; establish list of harmful species according to habitat type and region. Likely to be yearly monitored.
2.2 Structural characteristics				
Basal area	$m^2\ ha^{-1}$	Forest inventory	Recommended	
Uneven structure	number of existing size classes	Forest inventory, Plot survey, LIDAR	Recommended	Establish diametric classes according to specific habitat and region. Related to vertical stratification.
Canopy cover	%	Forest inventory, Plot visual survey, LIDAR	Essential	Compatible with the presence of gaps. Likely to be yearly monitored.
Canopy height	m	Forest inventory	Recommended	
Vertical stratification	(1) number, (2) cover (%) of layers	Plot survey, LIDAR	Essential	Related to non-coetaneous forests. Layers include: (canopy, sub-canopy, shrubs, herbs, bryophytes)
Canopy gaps	number ha^{-1}	Site survey, LIDAR	Specific	Refer to openings providing habitat and regeneration. Establish size range according to specific habitat and region
Large living trees	number ha^{-1}	Plot/Site survey, LIDAR	Essential	Establish criteria of large trees according to specific habitat and region
Deadwood (standing and lying)	m^3 ha-1	Plot survey	Essential	Establish criteria of categories according to specific habitat and region. Standing and lying deadwood could be measured separately as suggested in the Nature Restoration Regulation (2024/1991)
Microhabitats	(1) presence, (2) richness ha^{-1}, (3) abundance in ha^{-1}	Plot survey	Recommended	Establish types of microhabitats according to specific habitat and region

Variables	Metrics & measurement units	Measurement procedures	Application	Considerations relating to methodologies
2.2 Functional characteristics				
Browsing	categories (absent, low, medium, high)	Plot survey	Specific	Establish criteria of categories according to specific habitat and region. Likely to be yearly monitored
Canopy health	(1) tree number %, (2) cover (%) of damaged tress	Plot survey	Essential	Include dead and alive trees with signs of decay or defoliation by abiotic or biotic agents above natural baseline. Likely to be yearly monitored
Canopy greenness (forest productivity)	NDVI, NDWI	Remote sensing	Recommended	Sometimes used as a proxy of productivity at landscape or regional scales, but subjected to saturation and phenological fluctuations. Likely to be seasonally monitored
Human-induced impact	(1) presence/absence, (2) intensity categories (detail type)	Plot/Site survey	Essential	Refer to frequentation (trampling, rubbish, etc.) and management (harvesting, clearing, grazing). Establish criteria of condition according to specific habitat and region. Likely to be yearly monitored
Regeneration of tree characteristic species	categories (absent, low, medium, high)	Plot survey	Essential	Refer to the list of characteristic species. Establish criteria of categories according to specific habitat, region and development stage of forest
Natural disturbance	intensity categories (detail type)	Plot/Site survey	Essential	Refer to non-human disturbances (windstorms, floods, wildfires)
Successional stage	categories (initial, intermediate, mature, senescent)	Plot/Site survey	Recommended	Integrative expert-based assessment, according to specific habitat and region
3. Landscape characteristics				
Patch size	(1) mean patch size (ha), (2) total area (ha)	Remote sensing	Essential	
Fragmentation	(1) effective mesh size (ha), (2) Orlóci index	Remote sensing	Essential	
Continuity of riparian vegetation	(1) length (mean, range); (2) width (mean, range)	Remote sensing	Specific	To be measured in riparian forests

[1] Species cover can be considered structural variables, as they reflect habitat structure and dominance patterns rather than mere composition.

Site surveys implies recording data from areas larger that standard plots (see section 3.5), and can be merged with plot-level surveys. Observations include measurement periodicity whatever different from the approximately 6-years period recommended to accomplish normative assessments.

3.2 Guidelines for the establishment of reference and threshold values, and obtaining condition indicators for the variables measured

The observed measurements of the condition variables need to be compared to reference values and critical thresholds, in order to assess the condition for each variable. A reference level is the value of a variable at the reference condition, against which it is meaningful to compare past, present or future measured values of the variable. The difference between the value of a variable and its reference level represents the distance from the reference condition.

Reference levels should be defined in a consistent and transparent manner across different variables within an ecosystem type, and for the same variable across different ecosystem types. This ensures that the derived indicators are compatible and comparable, and that their aggregation is ecologically meaningful.

Reference levels are usually set with high and low levels reflecting the limits or endpoints of the range of a condition variable that can be used in re-scaling. For example, the high level may refer to a natural state and the low level may refer to a degraded state where ecosystem processes are below a threshold for maintaining function (Keith et al., 2013, United Nations et al., 2021).

Establishing reference values and thresholds is necessary to determine whether habitats are in good or have become degraded. Reference values represent the desired state of an ecosystem, often reflecting intact or minimally disturbed conditions. Thresholds critically determine benchmarks for assessing favourable habitat condition.

Nevertheless, the reference values and thresholds determining favourable condition in forest habitats intrinsically have a disparity according to the variable, the specific habitat, the contextual biogeographical gradients, and the historical, cultural and socio-economic background. Thus, this guideline does not intend to provide specific reference values and thresholds, but to define the main criteria and provide guidance on the establishment of them that would help determining condition, considering their ecological variability of the habitats across their range.

As for the variables, the harmonization of the reference values must consider a set of **common requirements**:

- For a given habitat, the final assessment of habitat condition and its trend through time, based on reference values and thresholds of the variables characterizing the habitat, should be equivalent for the different MSs, after accounting the contextual factors of each MS (e.g., climate).
- Reference values and thresholds need to be tested with sufficient data sets, which include full range of habitat conditions – from degraded habitats to best quality ones.
- Reference values and thresholds need to consider the natural variability of the habitats across their range, and different thresholds or reference values and thresholds for the same habitat in different MSs or regions within a MS can be appropriated.
- The establishment of reference values requires a source of information external to the evaluated site, which by different ways provides insight about the habitat condition that can be translated to values of the variables characterising the habitat.
- The reference values should fulfil the criteria of validity (connection to relevant ecological integrity), robustness (reliability), transparency, and applicability (Czúcz et al., 2021, Jakobsson et al., 2020).

- A description of the methodology for establishing the reference values and threshold applied by each MS for each variable must be provided, justified and perfectly understandable.
- The methodologies should be suitable to be regularly evaluated and improved according to the best available scientific knowledge and any modifications made, and the impact these may have on previous monitoring work, must be communicated.
- A reference library and the establishment of indicator thresholds for different habitat types across regions should be implemented, considering the respective ecological characteristics and natural variability.
- Common training or guidance on setting reference values and threshold should be programmed for experts from the different MSs in order to achieve full harmonisation.

Several types of approaches have been recognized to estimate reference values (Stoddard et al. 2006, Jackobson et al., 2020, Keith et al., 2020), which can be applied to assess forest habitats. Here we synthetise them in six broad categories: (1) absolute biophysical boundaries, (2) comparison to reference empirical cases of the respective forest habitat (areas, communities) that are considered to be in good condition, (3) comparison to undisturbed cases, (4) modelling and extrapolating variables - condition relationships, (5) statistical assessments, and (6) expert judgement. All these approaches should be based on scientific literature.

We discard the convenience of approaches using values in baseline year as reference values to establish good condition since they do not ensure the existence of favourable condition in the selected baseline year, and considering the difficulty to obtain reliable, appropriate historical data (Jakobsson et al., 2020). The use of historical period (e.g., previous to the pre-industrial state) as a reference state (Stoddard et al., 2006; Keith, 2020) corresponds to the baseline approach, although it is also related to comparisons to undisturbed cases (see below). Nevertheless, when variables in a baseline year are documented as corrresponding to a favourable condition, comparisons to such year can be convenient for synthesized trend analyses. Similarly, when historical, pristine states can be well documented, they can be used as reference states, following the approach that use comparison to undisturbed sites.

Absolute biophysical boundaries

They correspond to situations in which observed values in the variables are outside the physical-chemical (e.g., soil pH, bare soil) or biotic limits (e.g., presence of alien species) that define the habitat, thus making a good condition of the habitat impossible (Jakobsson et al., 2020). Therefore, they correspond to negative impacts of the variable on the condition of the habitat.

- Advantages: this approach establishes robust, transparent criteria clearly connected to the ecological integrity of the habitat.
- Disadvantages: it applies to a small number of variables with negative impacts in good condition.

Comparison to empirical cases considered to be in good condition

This approach is based on the identification of areas or communities that are considered to be in good condition (Stoddard, 2006, Jakobsson, 2020, Keith et al., 2020, FUNGOBE, 2024). These cases will provide the reference values. Therefore, their selection and the existence of a sufficient number is a key element for providing reliability to the estimates of the reference values (Soranno et al., 2011). Although this approach may seem obvious, it suffers from the difficulty of finding these areas in environments that have been historically altered. This problem may be afforded with caution by accepting as favourable some situations with the best possible forest management practices ("best attainable condition") (Stoddard, 2006).

- Advantages: assuming that data from cases in good condition can be obtained, this approach empirically presents a high level of validity and reliability by linking the values of the variables to the habitat condition.
- Disadvantages: there are methodological difficulties in finding enough cases in good condition that can be used to establish reference values.

Comparison to cases with a natural disturbance regime

This approach is related to the previous one, if assuming that most human-induced disturbances decrease the quality of habitats. This argument is in general valid in humanized environments, and can be related to historical references in which human pressure was not so accentuated (Stoddard 2006). But, perturbations imbedded into natural disturbance regimes constitute a sign of naturalness, thus, likely good condition. Indeed, a certain degree of disturbance can be an indicator of good conservation status by favoring the creation of microhabitats, thus promoting biodiversity, and the regeneration of characteristic species of the habitat (Table 5) (Keith et al. 2020).

Regarding the previous approach, historical criteria can be established with the absence of management or human intervention that determines these areas ("primary" forests, sensu Sabatini et al. 2017) and presents a direct connection with old-growth and primeval forests (Wirth et al. 2009, Burrascano et al. 2013, see also Buchwald 2005), which are assumed to be in good condition. However, in territories with high anthropogenic pressure it may be difficult to find these unaltered forests for some habitats (Keith et al. 2020). On the other hand, using a relatively short time period for defining the undisturbed state may ignore legacies of disturbances that last over time (Alfaro-Sanchez et al., 2019).

- Advantages: this approach is transparent by establishing clear criteria for empirically defining reference undisturbed cases, and can take advantage of large-scale sources of information on disturbance and management.
- Disadvantages: there are flaws in the validity of the approach, if we assume that any level of disturbance reduces habitat quality; applicability may be hampered by difficulties in finding, for some habitats, sufficient undisturbed habitat areas or those with natural disturbance regimes.

Modelling the relationships between variables and condition

This approach assumes a relationship between the values of the variables and the condition of the habitat. When determining reference values and thresholds, the use of models that describe the relationship between variables and condition has a conceptual basis shared with methodologies based on dose-response curves. These models assume cases of good condition to be correlated with the levels of the condition variable. The advantage of modelling is that it infers reference values when empirical good condition or undisturbed cases are not available. Thus, existing information for some empirical cases can be extrapolated to other situations, such as certain locations in the climatic gradient.

There are different modeling procedure and different functions, which can be linear, saturated or humped, can be used (Stoddard et al. 2006, Jakobsson et al., 2020). For example, dead wood volume in pristine forests can be modeled along productivity gradients to establish reference values of that variable in climatic conditions where such unaltered forests do not exist (Jakobsson et al., 2020). Correlative climate niche models can also be used to calculate the suitability of sets of species at any point on the climate gradient (Jakobsson et al., 2020) or other variables that characterise the habitat. There is also the possibility of creating models in which the condition is inferred from the value of other variable different from the variable directly describing condition. For example, some biodiversity-related condition variables may be inferred by pollution levels. This approach, however, should be considered with caution to avoid tautological inferences involving variables that describe pressures. Overall, though these approaches have a functional basis for establishing reference values, they require a number of assumptions that often need expert judgment.

- Advantages: modelling approaches are flexible, transparent and comprises a set of different procedures based on functional connections between variables and condition (supporting the validity criteria), taking advantage from scientific knowledge developed in different disciplines. They allow reference values to be obtained when empirical cases of good or undisturbed condition are insufficient.
- Disadvantages: the information available for building models is insufficient or unreliable for many variables, the outputs are highly sensitive to the modelling procedure and to assumptions, and expert judgement is ultimately needed for the different steps in the modelling procedures.

Statistical assessments

This approach is based on quantitative information from databases, which report the distribution of variables in a certain habitat. It assumes that higher values of the variables correspond to a good condition, when they exhibit a positive relationship, and vice versa. For these variables, high percentile values or confidence intervals (e.g. 95%, Jakobsson et al. 2020) or differences with the maximal observed values (Storch et al., 2018), can be applied. For those variables with a negative impact, low (e.g., 5%) or minimum values can be applied, while for variables with a humped impact on the habitat condition (e.g., gap occurrence, browsing) a combination of high and low percentiles can be used. This approach is particularly applicable for variables that can be obtained from forest inventories (Corona et al., 2011; Storch, 2018, Pescador et al., 2022), or when empirical cases of good condition providing reference values are not available. However, it may not be informative about the state of the habitat when it is in poor condition throughout the assessed territory as a whole. In other words, this approach is not based directly on reference situations of good condition, but on statistical inferences. These inferences, in turn, are subjected to the constraints of the sampling carried out to obtain the reference database.

- Advantages: this approach is reasonably applicable with statistical training, and is also transparent, replicable and moderately subjective.
- Disadvantages: the existence of appropriate, quantitative datasets providing the reference state is compulsory for applying this procedure. Its reliability therefore depends on the distribution of the condition classes (from bad to good) in the dataset and its correspondence to empirical situations of good condition. Thus, it may produce under- or over-estimations of good condition, and may also be sensitive to habitats that are poorly represented in the dataset.

Expert judgement

The setting of reference values and thresholds by experts is common practice, particularly when other sources of information are lacking for certain non-abundant habitats, and experts have developed an empirical understanding of habitat condition. However, there is often a lack of transparency and the level of knowledge of the experts may be insufficient. Therefore, in some ways it can be considered as a last option for many variables. However, for other variables, such as the assemblies of characteristic species, the successional stage, the existence of microhabitats or the characteristics of regeneration, this approach may be suitable for establishing reference values and thresholds. In any case, it is advisable to develop protocols based on consensus and consultation with several experts with comparable experience, establishing rules (e.g., through standardised questionnaires) and detailing how these experts arrived at their conclusions (Stoddard et al., 2006). Finally, the lack of experts in certain habitats can pose an additional difficulty for the correct use of this approach.

- Advantages: this approach can be easily applied and is frequently used, taking advantage of previous experience.
- Disadvantages: it exhibits an undesirable degree of subjectivity and low transparency, resulting in limited replicability and reliability. Its application may suffer from scarcity of experts for given habitats and MS.

Table 7 shows a tentative insight of the approaches for establishing thresholds and reference values applicable to the proposed variables for the purpose of harmonisation (see Table 6), based on the procedures followed by MSs and the existing literature. In fact, a combination of approaches is recommended to better inform the setting of reference levels and thresholds, given the degree of uncertainty when setting reference levels. The different approaches described are not exclusive, instead they are often combined. For example, expert judgment is necessary when establishing reference cases for good condition or for certain decisions in modeling the relationship between variables and condition. In fact, modeling-based approaches complement those based on good condition or undisturbed cases, and can also be combined with statistical approaches.

Additionally, owing to the different metrics and magnitudes applied to the variables that characterise the habitats, the values obtained from their measurement require some form of **standardisation**. This procedure ultimately allows that evaluations could be carried out in different habitats and along biogeographic gradients, as well as that monitoring could assess the evolution of conservation status. In the assessment of habitat condition, each characteristic and associated variable is likely to involve the use of different measurement units. These are normalised by reference levels; thus, reference values determining habitat condition can be compared with each other. The values obtained from the measurement for the variables are scaled according to their reference levels, thus normalised to a common scale and direction of change, and can then be combined to form a composite index or to obtain an overall result of the assessment, using appropriate aggregation approaches (see further details in Section 3.3. on Aggregation).

The evaluation of the condition of the habitats is based on determining whether the variables used in the assessment indicate good or not good condition. Nevertheless, it is common practice to define more than two categories in the assessment of each variable, e.g. good, medium, bad, as observed in the analysis of methodologies used by the MSs. Different criteria are applied to attribute these condition categories according to the characteristics of each variable, for example, whether they are categorical (e.g. no alien species allowed), or quantitative variables which may obey to linear or non-linear relationships with the condition (Jakobsson et al., 2020). This assimilation of the values (quantitative or categorical) of the variables to the condition categories (e.g. good, medium, bad) would correspond to the scaling necessary to later evaluate them jointly, through aggregation procedures (see further details in Section 3.3. on Aggregation). Thus, these variable condition categories can be translated to values, such as good=2, medium=1, bad=0. Alternatively, when quantitative values for the variables are available, they can be directly standardized to apply aggregation procedures.

Table 7. Tentative insight of criteria for the establishment of thresholds and reference values to determine favourable condition, applicable to the proposed variables to assess forest habitat condition

Dark grey indicates preferred or commonly applied criteria; light grey denotes additional criteria.

Type of characteristics / Variables	Biophysical boundaries	Comparison to good condition cases	Comparison to undisturbed cases	Modelling variables - condition	Statistical assessment	Expert judgement
Abiotic characteristics						
Physical state characteristics						
Groundwater level	Dark grey	Light grey	Light grey	Dark grey		Light grey
Bare soil	Dark grey	Dark grey	Dark grey			
Litter cover		Dark grey	Dark grey			
Litter depth		Dark grey	Dark grey			Light grey
Chemical state characteristics						
Soil organic matter		Dark grey	Dark grey	Dark grey	Light grey	Light grey
Acidity	Dark grey					
Nutrient content	Dark grey					
Bbiotic characteristics						
Compositional characteristics						
Characteristic species		Dark grey	Dark grey	Light grey		Dark grey
Animal species		Dark grey	Dark grey	Light grey		Dark grey
Tree richness		Dark grey	Dark grey	Dark grey	Dark grey	
Shrub richness		Dark grey	Dark grey		Dark grey	Dark grey
Alien species	Dark grey					Light grey
Harmful species		Dark grey		Dark grey		Dark grey
Structural characteristics						
Basal area				Light grey	Dark grey	
Uneven structure		Dark grey	Dark grey		Dark grey	Light grey
Canopy cover			Light grey	Dark grey		Dark grey
Canopy height			Light grey	Light grey	Dark grey	
Vertical stratification		Dark grey	Dark grey			Light grey
Canopy gaps		Dark grey		Dark grey		Dark grey
Large living trees		Dark grey	Dark grey		Dark grey	Light grey
Coarse woody debris			Dark grey	Dark grey	Light grey	
Microhabitats		Dark grey	Dark grey	Dark grey		Dark grey
Functional characteristics						
Browsing		Dark grey		Dark grey		Light grey
Canopy health	Light grey	Light grey		Dark grey	Dark grey	Dark grey

Type of characteristics / Variables	Biophysical boundaries	Comparison to good condition cases	Comparison to undisturbed cases	Modelling variables - condition	Statistical assessment	Expert judgement
Canopy greenness						
Human-induced impact						
Regeneration of tree characteristic species						
Non-human disturbance						
Successional stage						
Landscape characteristics						
Patch size						
Fragmentation						
Continuity of riparian vegetation						

3.3 Guidelines for the aggregation of variables at the local level

Ecological assessments require the integration of physical, chemical, and biological quality elements. The choice of aggregation method of partial assessments into an overall evaluation has been widely discussed within the scientific community, as it can significantly influence the final outcome. Applying appropriate aggregation approaches is essential for categorising condition at the local scale as good or not good, since the proportions of habitat type area in good/not good condition is the key information needed for evaluating the conservation status of structure and functions at the biogeographical level.

Various approaches can be used to integrate the values of measured variables into an overall index reflecting the condition of habitat types at the local scale (e.g., monitoring plot, station, or site).

3.3.1 Overview of aggregation methods

Based on the literature (e.g., Langhans et al. 2014, Borja et al. 2014), two main aggregation approaches can be distinguished: the one-out, all-out rule (minimum aggregation) and additive aggregation (e.g., simple addition, arithmetic mean, geometric mean).

Further information on aggregation approaches and methods is provided below.

For the minimum aggregation, the aggregated value is calculated as the minimum of the values of the measured variables. The **one-out, all-out (OOAO) rule** has been recommended for assessing ecological status under the Water Framework Directive (CIS, 2003). The principle behind this minimum aggregation method is that a water body cannot be classified as having good ecological status if any of the measured quality elements fail to meet the required threshold. This is considered a precautionary and rigorous approach, but it has also been criticised for potentially underestimating the true overall status.

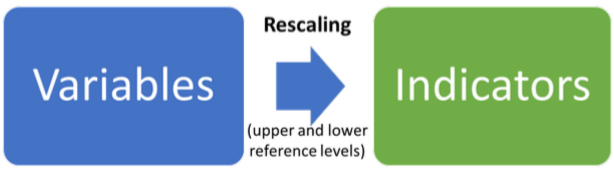
A precautionary OOAO approach is also used in the aggregation of parameters when assessing conservation status under the Habitats Directives, the IUCN Red List of Species and the IUCN Red List of Ecosystems.

Conditional rules require that a certain proportion of variables meet their respective thresholds in order for the overall assessment to achieve a good condition rating. For example, the overall status may be considered as not good when a specific number of variables fail to meet their thresholds.

Simple additive methods calculate an aggregated value as the sum of the *n* values (*vi*) of the variables. **Averaging approaches** are among the most commonly used methods for aggregating indicators. These include straightforward calculations such as the arithmetic mean, weighted average, median, or combinations thereof, to produce an overall assessment value.

Normalization of variables values (rescaling). In the assessment of habitat condition, each characteristic and associated variable is likely to involve the use of different measurement units. To ensure comparability, the measured values of variables are often normalised to a common scale (e.g., 0 to 1 or 0 to 100). This involves rescaling the raw data based on reference values or thresholds that define the boundary between good and not good condition for each variable. By rescaling the condition variables, indicators are standardised to the same scale, making it possible to aggregate them into condition indices that reflect the overall condition at a given plot or location.

Figure 2. Example of deriving condition indicators by rescaling the values obtained for variables, based on upper and lower reference levels



$$Condition\ indicator = \frac{(V-VL)}{(VH-VL)} \quad \text{[Equation 1]}$$

Where:

- V is the measured/observed value of the variable,
- VH is the high condition value for the variable (upper reference level),
- VL is the low condition value (lower reference level).

Source: Vallecillo et al. (2022)

Weighting. Differential weighting of indicators may be applied when calculating sums, means, or medians. The choice of weighting system should reflect the relative importance of each indicator in determining the overall condition of the ecosystem. Ideally, the approach should be supported by a clear scientific rationale and informed by input from ecologists with expertise in the relevant ecosystem types. However, a robust basis for assigning weights is not always available. In such cases, weighting often relies on expert judgment, which can be subjective, as expert opinions may differ considerably.

3.3.2 A simple procedure for the aggregation of measured variables

For simplicity, a basic quantitative aggregation method is proposed in these guidelines to integrate all essential and specific variables measured to assess the forest habitat condition. The method should be applied consistently across the habitat range in order to obtain comparable results.

An averaging approach is proposed to determine the habitat condition at the local scale, with a normalisation of the values obtained for each of the measured variables.

Step 1 – Normalisation of the variables

The quantitative values obtained for each variable should be normalised by rescaling based on reference values (as described above). The value of each variable will be thus in the range from 0 to 1.

Step 2 – Aggregation of normalised variables by averaging approach

For the sake of simplicity, and considering the difficulties to suggest a more complex method or index, we describe here a preliminary proposal for aggregation based on the arithmetic mean with normalisation of the values obtained for each of the measured variables, which could be used to determine the habitat condition at the local scale, as summarised in the following equation:

$$Local\ condition = \sum_{1}^{n} v_i/\mathrm{n}$$

Where n is the number of variables, v_i the rescaled value of the corresponding variable (between 0 and 1). The aggregated value would range between 0 and 1.

An alternative method would be to use the weighted average, in which the weight of each variable should be decided, justified and agreed upon for each habitat type by all the MSs that would apply the method. This method can be formulated with the following equation:

$$Local\ condition = \sum_{1}^{n} v_i * w_i/\mathrm{n}$$

Where n is the number of variables, v_i the rescaled value of the corresponding variable (between 0 and 1) and w_i the corresponding weight, with $\sum w_i = 1$. The aggregated value would range between 0 and 1.

This second method, however, presents some difficulties when assigning weights to the variables, which must be based on a proper evaluation of their importance and influence on the habitat condition, based on a robust scientific knowledge. It also requires reaching a consensus on the weights assigned to the variables measured for each type of habitat, among all the countries that must assess its condition. This is a crucial aspect to obtain comparable results in the assessments carried out by all the Member States.

Step 3 – Identify the threshold to determine good/not good condition at the local scale

Finally, a threshold must be applied to the aggregated value to distinguish between good and not good overall condition. This is a crucial step and, wherever possible, this threshold should be established based on empirical data from reference localities in good condition and from localities showing a degraded state. Where such reference localities are not fully available, modelling to obtain such thresholds could be applied.

3.4 Guidelines for aggregation at the biogeographical region scale

As a minimum requirement, Member States must follow the recommendations of the Art. 17 reporting guidelines for the period 2013-2018, which establish that “if 90% of the habitat area is considered as in ‘good’ condition, then the status of the ‘structure and functions’ parameter is ‘favourable’. If more than 25% of the habitat area is reported as ‘not in good condition’, then the ‘structure and functions’ parameter is ‘unfavourable-bad’. However, MSs may improve these thresholds further, usually in a more restrictive way. Thus, the “one-out, all-out” approach (minimum aggregation, as already described) can also be considered appropriate. Overall, these rules highlight the importance of a sampling design that ensures sufficient representativeness of the total habitat area and diversity (see section below).

3.5 Guidelines on general sampling methods and protocols

Some recommendations of sampling methods and monitoring protocols for the forest habitat types, based on the protocols used in the different MSs, are summarised below.

The sampling design must be the same for all the selected localities of a forest habitat type. Most long-term monitoring protocols use **permanent plots** established by means of either systematic, stratified or random selection (see also section 3.6).

3.5.1 Sampling protocols

Plot size and shape must ensure consistency. **Fixed-radius nested circular plots** are the most used for forest monitoring (Figure 3). They allow detailed sampling of different forest components within the same plot and increase sampling efficiency by capturing data at multiple scales. The plot size should balance the need for statistical reliability with the practical constraints of fieldwork (accessibility, availability of resources, etc.).

Riparian forests may, however, require specialised plot designs and sizes to capture the unique ecological characteristics and gradients of these areas. For this type of forest, transect-based plots established along the water body and large enough to capture the gradient from the water to the forest are recommended (Figure 4). Transect length and plot dimensions depend on the width of the riparian zone. Gridded transects facilitate spatial analysis and mapping. In addition, a nested plot design is also recommended whenever possible.

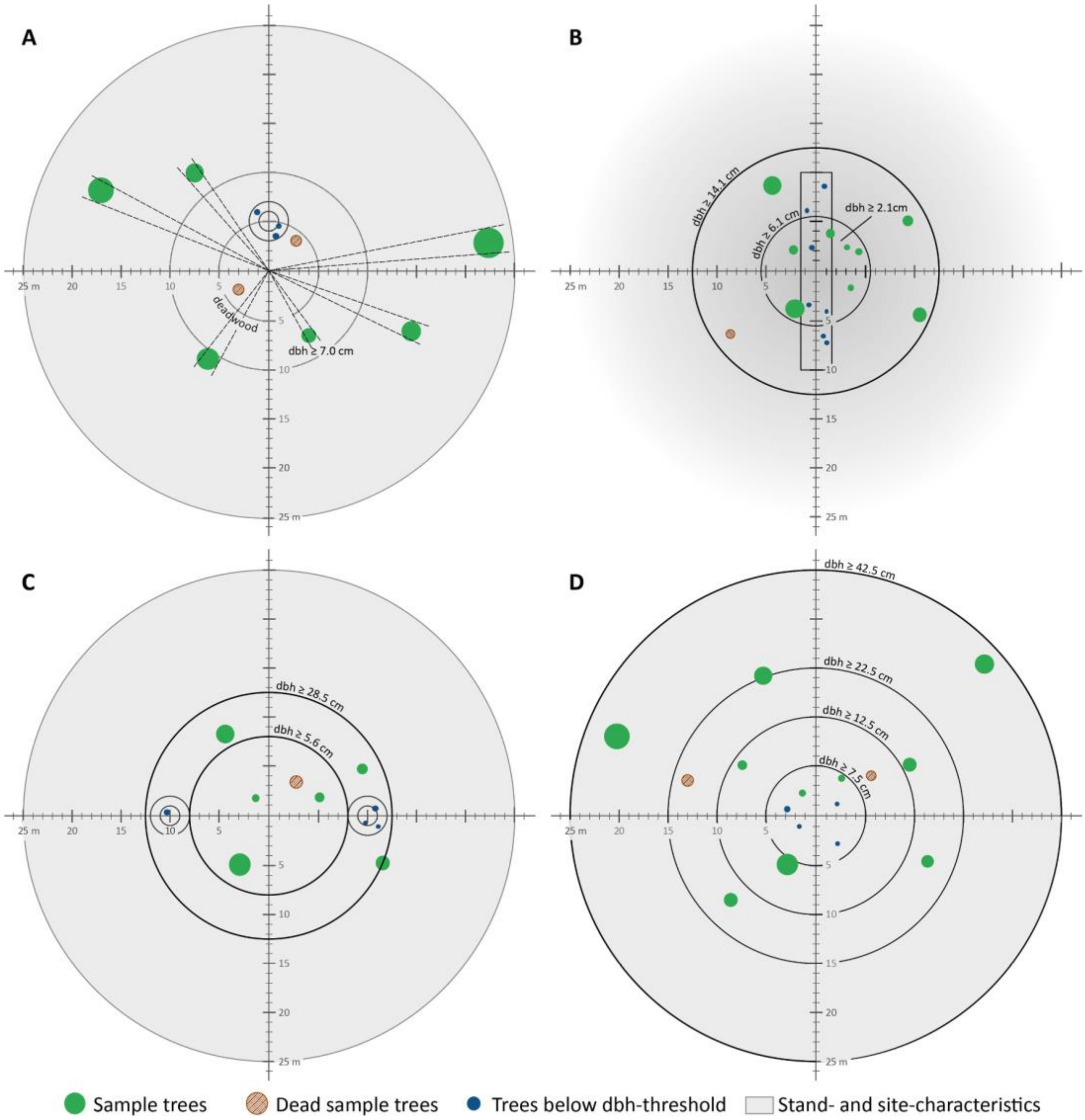
Finally, since boundaries of riparian forests can change significantly due to meandering rivers, flooding, erosion, or deposition., incorporating dynamic spatial references could improve the ability of riparian forest inventories to reflect real ecological conditions over time. In this sense a methodology for coastal habitats available in Sweden (Adler et al., 2020; Hedenås et al., 2024) could serve as a good example to apply to riparian forest. This methodology does not treat coastal habitats as fixed spatial entities, but rather as **dynamic systems** whose locations shift over time. It anchors transects to **natural, moving reference points**, such as the current mean water level, and adapts field inventories based on recent aerial imagery and on-site observations. This allows to capture habitat changes caused by coastal dynamics, sediment transport, and watercourse shifts.

3.5.2 Monitoring frequency

Article 17 of the Habitats Directive requests a maximum period of six years. However, this period can be completed using different approaches depending on the resources of MSs. Thus, not all permanent plots and not all variables must be measured every six years. MSs may establish a large number of monitoring plots, selecting a subset to be surveyed each season, to ensure that they have an adequate number of plots that are fully monitored at least every six years. With regard to variables, many of them are suitable to be surveyed every five-six years, but some abiotic functional variables, canopy cover and some compositional variables (typical, alien and harmful species) and functional (browsing, canopy health and greenness) and human-induced impacts should ideally be surveyed every year.

Given their dynamic nature, riparian zones are recommended to be surveyed every two years. In any case, **adaptive monitoring** is always recommended, thus allowing flexibility in frequency based on initial findings.

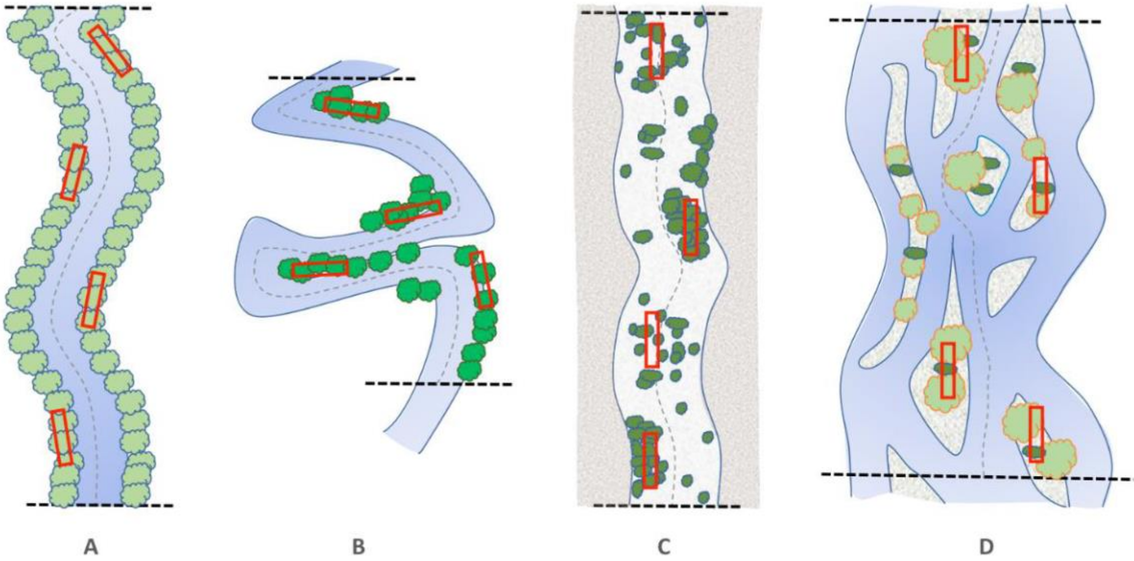
Figure 3. Examples of nested circular plot configurations used for National Forest Inventory (NFI) monitoring, harmonised for growing stock monitoring



A: Germany – angle-count sampling and concentric regeneration plots; B: Latvia and Lithuania – two concentric circles, with one quarter of the inner circle serving as a third tree-sampling unit, and rectangular regeneration plot; C: Romania – two concentric circles and two regeneration plots; D: Spain – four concentric circles and an inner circle serving as a regeneration plot.

Source: Gschwantner et al (2022)

Figure 4. Example of delimitation and location of transects (0.5 km) and plots (50×5 m; red rectangles) for riparian forests in four scenarios.



A: uniform gallery forest on both banks of a river; B: discontinuous hydrophilic forest in a meandering sectio;. C: shrubby vegetation on the bed of a ravine; D: open woodland on unstable sediments of the main channel in a braided river. Elements of the diagrams are not to scale.

Source: Lara et al (2019)

3.5.3 Data collection

With regard to sampling design and data collection protocols, several authors have highlighted the potential of European **National Forest Inventories (NFIs)** for encompassing harmonised estimates for assessing the conservation status of forest habitats at different scales (Alberdi et al., 2019).

In the EU, there already exists a harmonisation process, initiated in the late 1990s (Tomppo et al., 2010), which was strongly promoted by the foundation of the European National Forest Inventory Network in 2003 (ENFIN, 2024).

General principles and a harmonisation approach have already been established and used in the Global Forest Resources Assessment 2000 (FRA 2000) (FAO, 2001) and the Temperate and Boreal Forest Resources Assessment 2000 (TBFRA 2000) (UNECE/FAO, 2000), and were also published for the subsequent assessments. In addition, several scientific papers have been published to promote the harmonisation process (e.g., Chirici et al., 2012, Gschwantner et al., 2022; Gschwantner et al., 2024; Avitabile et al., 2024). In fact, out of the 27 European MSs, 23 have an ongoing NFI.

In this context, it is highly recommended the use of NFIs for collecting data for assessing and monitoring forest conservation status, incorporating in these inventories those variables characterising habitat condition which have not yet been surveyed. However, owing to the NFIs' regular sampling method, there are uncommon forest habitat types that may remain poorly represented in the NFIs' surveys. In these cases, other specific additional sampling techniques may be required (Pescador et al., 2019b).

3.6 Selecting monitoring localities and sampling design

The selection of localities for sampling - along with the sample size (number of plots) and power (statistical significance) - is crucial for ensuring the representativeness of the results obtained in the assessment and the monitoring of each habitat at the biogeographical scale. The selection should be grounded in a comprehensive inventory, supported by detailed cartography and ecological characterization of habitat types and their variability.

Identifying and selecting localities for sampling requires a systematic approach to ensure that the chosen sites provide comprehensive and representative data on habitat condition within the biogeographical region. Sampling localities should reflect the full range of habitat diversity, as well as environmental gradients, including variations in elevation, soil types, and climate. Moreover, sites should be selected both inside and outside protected areas. This requires a sound understanding of the distribution and variability of each habitat across its range, including the identification of ecotypes or subtypes, where relevant.

3.6.1 Criteria for selecting monitoring localities

The main criteria for selecting monitoring localities are summarised below.

- **Ecological variability**: Localities must represent the full range of ecological diversity and variability within the habitat type. Selection should include different ecotypes or subtypes, successional stages, and reflect key environmental gradients such as altitude, soil type, moisture levels, geomorphological features, and topography.
- **Spatial Coverage**: Adequate spatial coverage is essential to capture habitat heterogeneity. Localities should be selected across the full geographical range of the habitat type within the region, ensuring they are well distributed and represent a significant proportion of the habitat's total occupied area.
- **Degree of conservation and exposure to pressures and threats**: The selection of monitoring localities should include areas with varying degrees of conservation and degradation, in order to capture the full range of habitat condition across its distribution. This includes both well-conserved areas with minimal human impact, and areas affected by degradation and subject to different pressures. To reflect the diversity of pressures acting on the habitat, localities should span a range of intensity levels – from low to high – and account for different sources of disturbance, such as urbanisation, agriculture, and climate change.
- **Presence inside and outside Natura 2000 sites***:* The assessment and monitoring of habitat conservation status must be carried out both inside and outside Natura 2000 sites. This requires selecting localities – and an appropriate number of plots – that reflect the proportion to the habitat's distribution within and outside the Natura 2000 network.
- **Habitat fragmentation at landscape scale**: Localities should be selected based on landscape metrics such as patch size and connectivity. Including both isolated and well-connected sites allows for the assessment of fragmentation effects on habitat condition. Understanding these patterns is essential for developing strategies to mitigate the negative impacts of habitat fragmentation.
- **Lack of Information**: Including areas where data are lacking contributes to building a more comprehensive dataset. Selecting localities in historically under-sampled regions ensures a more balanced and complete understanding of habitat condition across its range. This helps to address data gaps and supports more informed conservation planning.

- **Accessibility and practicality:** Monitoring localities should be accessible for regular field visits, taking into account logistical factors such as distance from roads and ease of access. Practical considerations also include the safety of field personnel and the feasibility of transporting equipment to and from the site.
- **Historical Data and existing monitoring sites:** Making use of existing monitoring sites with historical data can strengthen the understanding of long-term trends and changes in habitat condition. Such sites provide valuable baselines for comparison and support more robust trend analyses over time.

3.6.2 Sample size

Once sampling localities have been identified for each habitat type, the minimum number of plots per locality – and across the biogeographical region – must be calculated to balance sampling effort with the need for representative data.

The **size of the sample** influences two statistical properties: 1) the precision of the estimates and 2) the power of the assessment to draw meaningful conclusions. The number of plots must be **statistically sufficient** to detect changes and trends with the desired level of confidence. Appropriate statistical methods should be applied to determine an adequate sample size.

Considering the heterogeneity of habitat types, it is highly recommended to consult a sampling statistician when determining sample size – that is, the minimum number of plots required to ensure representativity and statistical significance.

Some key elements for ensuring proper representation of habitat condition in the sample are summarised below.

Box 6. Key elements for statistical representation

Sample size and distribution:

- The number of localities and plots should be sufficient to provide a statistically robust sample size. This ensures that the collected data can be generalised to the entire habitat type within the region.
- Statistical methods such as stratified random sampling are often applied to ensure that all habitat subtypes and environmental gradients are adequately represented.

Sampling design:

- Within each sampling area or locality, multiple plots are established to collect detailed data on vegetation, soil, and other ecological indicators. The number and distribution of plots depend on the size of the habitat patch and its internal variability.
- Sampling areas (e.g., plots, transects) should be laid out with consideration of the main ecological gradients, such as altitude, moisture, and exposure to sea influence.

Replication and randomisation:

- Replicating sampling units within each locality and randomising the location of sampling plots help reduce bias and increase the reliability of the data.
- Randomised plot locations also ensure that sampling captures the natural variability within the habitat.

3.7 Use of available data sources, open data bases, new technologies

3.7.1 New technologies

Remote sensing technologies (aerial photography, laser scanning and satellite imagery) are based on radiation from different wavelengths that allow characterisation, e.g., greenness of canopy or superficial soil content. Remotely-sensed data have a major advantage in that they are available everywhere and at a higher temporal resolution than field sampling. For this reason, they have been used for the large-scale monitoring of health canopy (Margalef-Marrasse et al., 2020) and disturbances impact (Senf, 2021) in European forests and they can potentially be used for habitat condition assessment, particularly for structural and functional (e.g., canopy loss) characteristics (Del Barrio et al., 2019), using a land condition map from NDVI indexes and climatic surfaces. There have been considerable developments in these technologies over recent decades, which has significantly improved the quality of data.

Aerial photographs contain spectral information at a very high resolution. Using overlapping photographs, a detailed canopy height model (3D model) at sub-metre level can be calculated by means of image matching. **Airborne laser scanning** provides information on height, and the resulting 3D model is typically of even higher quality than that obtained from fieldwork. It allows the creation of a digital terrain model, which is highly useful for obtaining vegetation height and for studying forest structure. The most widely-known technology of this type is LiDAR. Most EU countries are at least in the process of completing their first Airborne Laser Scanning campaign, providing large-scale wall-to-wall digital terrain models. Thus, in the next future remote sensing methods, particularly LIDAR, will be regularly used. Finally, **satellites**, such as Sentinel-2 of the Copernicus programme, can provide complete coverage every five days (cloud conditions permitting). Images from optical satellites have a much lower spatial resolution than aerial photographs but a much higher temporal and spectral resolution. Radar satellites, such as Sentinel-1, actively scan the Earth's surface and are therefore less dependent on weather conditions than optical satellites, adding complementary information about the structure and moisture content of objects on the surface. Although remote sensing technologies offer high resolution layers, reliability in terms of some disturbance agents and the relationship between the state of the forest canopy and biodiversity is still limited. Moreover, remote sensing technologies have to statistically account for field data for training, calibration and validation.

3.7.2 International programmes and open data sources

International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests)[11] aims for a comprehensive compilation of information regarding the condition of forests in Europe and beyond. Among other information, the Network provides information on forest health and vitality; for example, regarding deposition of atmospheric pollutants, condition of forest soils, defoliation and forest damage.

European Long-Term Ecosystem Research (eLTER) is a state-of-the-art research infrastructure mainly aimed at facilitating high impact research and new insights about the compounded impacts of climate change, biodiversity loss, soil degradation, pollution and unsustainable resource use in terrestrial, freshwater and transitional water ecosystems. It includes the DEIMS-SDR (Dynamic Ecological Information Management System - Site and dataset registry) that gathers data from a wide range of long-term ecosystem research sites (including each site's location, ecosystems, facilities, parameters measured and research

[11] http://icp-forests.net/

themes) around the globe, as well as data from people and networks associated with them.

EUDAT Collaborative Data infrastructure[12] is an infrastructure of integrated data services and resources supporting research in Europe. It comprises projects that could provide important information for forest monitoring. For example, the European Network for Earth System Modelling (ENES) is developing a common climate and Earth system modelling research infrastructure in Europe, integrating the European community on Earth (climate) System Models (ESMs) and their hardware, software and data environments.

Europa Biodiversity Observation Network (EuropaBON)[13] aims to identify user and policy needs for biodiversity monitoring and to investigate the feasibility of setting up a centre to coordinate monitoring activities across Europe. Thus, it is an essential tool for surveying existing monitoring initiatives, including long-term ecosystem, remote sensing and citizen science initiatives, and assessing how these can contribute to the production of comprehensive biodiversity information that can be used for forest monitoring.

Forest Information System for Europe (FISE), developed by the European Environment Agency (EEA), collects and disseminates information on forest conditions across EU MSs[14]. The European Commission is preparing a new law on a monitoring framework for resilient European forests that will provide open access to the status and trends of EU forests. This law will strengthen the FISE as common database on forest information in Europe.

Forest Resources Assessment (FRA) by the FAO: The Food and Agriculture Organization (FAO) of the United Nations conducts the Global Forest Resources Assessment every five years. This comprehensive assessment involves data collection on forest extent, condition, management and use in participating countries[15].

Global Forest Watch (GFW) and Forest Watcher: These tools developed by the World Resources Institute (WRI) provide near-real-time monitoring of forest conditions using satellite data. GFW offers a platform for tracking deforestation, forest fires and other disturbances worldwide[16].

Finally, in the last few years, different **datasets related to species composition** have become available. Some of these, such as FloraVeg[17], provide indicator values for European vascular plants for light, temperature, moisture, soil reaction, nutrients, salinity, disturbance severity, disturbance frequency, mowing frequency, grazing pressure and soil disturbance. Other datasets provide species functional traits that allow the monitoring of forest functions. For example, FloraVeg also provides information about life forms and seed dispersal distances and modes for European plant species. In addition, there are other specific plant trait databases that cover a wider range of functional traits, such as TRY[18], LEDA[19] and BROT[20].

[12] https://eudat.eu/
[13] https://europabon.org/
[14] https://forest.eea.europa.eu
[15] https://www.fao.org/redd/areas-of-work/national-forest-monitoring-system/en
[16] https://www.globalforestwatch.org/
[17] https://floraveg.eu/download
[18] https://www.try-db.org/TryWeb/Home.php
[19] https://uol.de/en/landeco/research/leda
[20] https://www.uv.es/jgpausas/brot.htm

4. Guidelines to assess fragmentation at appropriate scales

Forest fragmentation is a critical aspect of habitat condition assessment and monitoring, as it affects biodiversity, ecosystem functions and species distributions. Fragmentation refers to the process whereby large, continuous forest areas are broken into smaller, isolated patches due to human activities or natural processes. This leads to reduced habitat connectivity, increased edge effects and habitat loss. As a result, highly fragmented landscapes typically show lower ecological integrity. Therefore, the assessment of habitat fragmentation will be integrated in the assessment of habitat condition along with habitat status and trends.

The assessment of forest fragmentation addresses different **spatial attributes** that are represented on forest maps: total forest area, average patch size, number of forest patches, spatial aggregation and/or dispersion of forest patches, compactness, number of forest adjacencies, number of forest perforations, inter-patch connectivity, distance, etc.

Forest fragmentation has different effects depending on the scale at which it is analysed. Thus, a **multi-scale approach** is recommended for increasing assessment effectiveness:

- **Local scale**: For assessing individual patches for edge effects, core area size and structural integrity of the forest.
- **Landscape scale**: For analysing the distribution of multiple patches across the landscape to assess habitat connectivity, corridor functionality and overall landscape integrity.
- **Regional scale**: For considering the bioregion, particularly to evaluate how larger drivers (e.g., climate change, regional land use) are contributing to long-term trends in fragmentation.

This multi-scale approach is also recommended when considering the temporal dynamics:

- **A short-term scale** provides insight into rapid changes (e.g., due to deforestation or land conversion), which may be relevant for intervention in high-risk areas.
- **A long-term scale** allows the tracking of gradual fragmentation processes such as urban expansion, infrastructure development and climate-driven habitat shifts.

4.1 Data collection and analysis

Remote sensing technologies (satellite imagery, aerial photography) and **Geographic Information Systems** are fundamental tools for assessing forest fragmentation. High-resolution satellite imagery (e.g., Sentinel-2 or Landsat) using time series can be used for mapping forest cover and changes over time. In addition, LiDAR data can be implemented for assessing forest canopy structure and for differentiating between forest core and edge areas.

Finally, GIS tools can be used for delineating forest patches and measuring their size, shape and distance from other patches. In this respect, different GIS-based tools or software are available for assessing forest fragmentation, e.g., FragStats[21], Conefor[22] and landscape metrics R package[23].

[21] https://www.fragstats.org/
[22] http://www.conefor.org/
[23] https://cran.r-project.org/web/packages/landscapemetrics/landscapemetrics.pdf

4.2 Connectivity and landscape-level metrics

At the local level, fragmentation assessment focuses on understanding the characteristics of individual forest patches and their immediate surroundings to assess patch irregularity and vulnerability to edge effects. Some metrics include patch size, shape complexity, perimeter-area ratio and Landscape Shape Index (LSI). Most can be implemented using basic GIS tools.

At the landscape level, the focus is on the distribution and connectivity of multiple patches across a larger area. Some metrics include:

- **Patch density**. It measures the number of forest patches per unit area. High patch density can indicate fragmentation.
- **Core area**. It identifies the amount of 'core' forest area (i.e. away from edges).
- **Connectivity/isolation indexes**. It assesses how isolated patches are from each other, using metrics such as Proximity Index and Patch Cohesion Index.

As a guidance on the **implementation of standard methods** and procedures for assessing the degree of forest fragmentation, the approach followed by FOREST EUROPE[24] for the State of Europe's Forests 2020 report[25] may serve as a useful example. In this report, the spatial forest coverage is assessed from the **Copernicus CORINE Land Cover** (CLC) dataset for the years 1990, 2000, 2006, 2012 and 2018. Spatially explicit maps and statistical summaries are derived at three reporting levels: CLC (entire CLC coverage), EU28, and country level.

Forest fragmentation is measured through its complement, forest connectivity, using the **Forest Area Density** (FAD) parameter (Voigt et al., 2019). FAD measures the spatial integrity of forest land cover and accounts for key fragmentation aspects, such as isolation of small fragments and perforations within compact forest patches (Maes et al., 2023). FAD is a landscape variable measured in a local neighbourhood area. It is defined as the proportion of all forest pixels within a fixed neighbourhood area. Measurements are conducted via a moving window algorithm to create a new map of forest area density. The area density map is then stratified by applying a threshold value of 40% to derive the two fragmentation classes **Separated** (FAD < 40%) and **Continuous** (FAD >= 40%). In a second step, the pixel-level FAD values are averaged for all forest pixels of a given forest patch (APP: Average-Per-Patch) resulting in a map showing the degree of forest fragmentation at the patch level. Statistics of the forest fragmentation status maps are summarised using the following parameters:

- **Proportion** [%] and **area** [ha] of fragmentation classes (i.e., separated and continuous).
- **Total forest area** [ha].
- Total **number of forest patches**.
- Average of **forest patch size** [ha] (APS) = total forest area / total number of forest patches.
- **FADAV** [%]: average FAD for all forest pixels in the original FAD image before conducting APP.

These parameters can then be classified into five sequential fragmentation classes: Rare (FAD > 10%), Patchy (10% <=FAD < 40%), Transitional (40% <=FAD < 60%), Dominant (60% <=FAD < 90%) and Interior (90% <=FAD <= 100%). These five classes give more information

[24] https://foresteurope.org/
[25] https://foresteurope.org/wp-content/uploads/2016/08/SoEF2020.pdf

than the original two classes (i.e., separated and continuous) (Table 9). This fragmentation assessment can be implemented in the free software *GuidosToolbox* (Vogt & Riitters, 2017).

Table 8. Example of landscape assessment sheet

Colour	Forest fragmentation	Forest connectivity	Forest cover	Forest Area Clustering (FAC)
	Very high	Very low	Rare	[0 ≤ FAC < 10] %
	High	Low	Patchy	[10 ≤ FAC < 40] %
	Intermediate	Intermediate	Transitional	[40 ≤ FAC < 60] %
	Low	High	Dominant	[60 ≤ FAC < 90] %
	Very low	Very high	Interior	[90 ≤ FAC ≤ 100] %

Source: Adapted from Vogt & Caudullo (2022)

Please see also the Technical Guidelines to assess fragmentation of habitat types (separate volume in this collection of Technical guidelines).

9230 Galicio-Portuguese oak woods with *Quercus robur* and *Quercus pyrenaica*
© F. Dominguez

5. Next steps to address future needs

These guidelines offer an assessment of the methodologies employed by EU Member States to assess the condition of forest habitats and a proposal to harmonize the existing procedures.

To ensure that habitat condition assessments are comparable across countries, it is essential to use common set of variables/indicators with well-defined metrics and standard measurement procedures. These should include physical, chemical, compositional, and functional variables to comprehensively evaluate the health of mire habitats. In addition, landscape variables complement the evaluation habitat condition at a broader scale.

Future needs to further progress this harmonisation include the following main steps:

- Promote the implementation of the proposals and recommendations presented in these guidelines in all EU MSs. Aligning the existing methodologies with EU biodiversity policies, particularly the Nature Restoration Regulation will be crucial in the coming years.
- Test the proposed set of variables with agreed measurement procedures and monitoring methods, including common protocols for sampling, while considering the particularities of different habitats and contextual factors at local and country level; this testing would be useful to identify gaps of knowledge, flaws of applicability, and robustness and reliability of results. The evaluation should provide recommendations to be further integrated in the harmonized procedure, as needed.
- Develop further, test and standardise the methods for the establishment of reference values and thresholds to determine good condition, for aggregation of results obtained from all the variables measured at the local scale and for each biogeographical region.
- Develop further and test the criteria for the selection of monitoring localities and sampling design to ensure a sufficiently representative sample that allows for proper aggregation of results at the biogeographical region level. Particular attention should be given o the use of national forest inventory systems (NFI).
- Promote harmonised methods for the use of typical species: clear criteria should be defined for selecting these species, along with the methodologies to assess their status and integrate the results into overall condition assessment for each habitat.
- Promote the use of common monitoring and sampling protocols, particularly with regard to the use of NFIs.
- Explore further the use of available data sources and remote sensing and other relevant technologies to collect data for the assessment of condition variables, and eventually encourage the use of these methodologies.
- Offer common training and guidance for experts from the different MSs on the measurement of proposed condition variables, setting reference values and thresholds, applying aggregation rules for variables at local and biogeographical level, and selecting monitoring localities.
- Reinforce monitoring the effects of climate change on forest habitat condition, assessing its impacts on forest habitats and their resilience.
- Support research about ecological processes and functions of forest habitats in Europe, and their vulnerability to threats and pressures in a context of climate and land use change, with particular focus on collecting information useful to establish reference values and thresholds of good condition in different habitat types and biogeographical contexts.

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