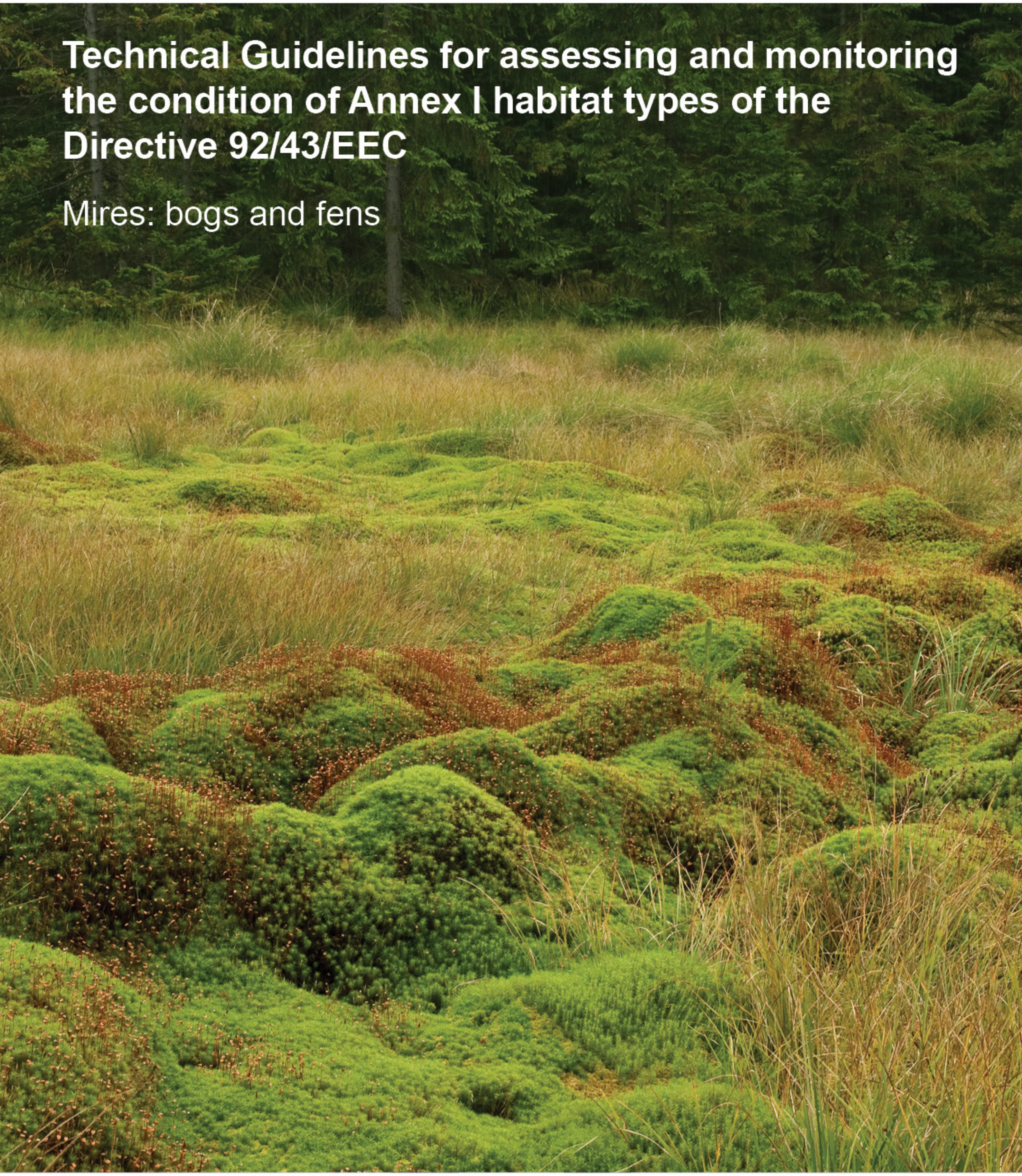
European Commission

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

## Mires: bogs and fens



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

# **Mires: bogs and fens**

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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

EU: European Union

HD: Habitats Directive

IAS: Invasive Alien Species

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) | | |

SEEA EA: System of Environmental Economic Accounting - Ecosystem Accounting

# Executive summary

Peatlands, or mires (actively forming peatlands), are a unique type of wetland characterised by the accumulation of peat. They are globally recognised for their crucial role in biodiversity conservation and carbon sequestration. However, over the centuries, they have been extensively drained for agriculture, forestry, and peat extraction, making them one of the most endangered habitats in Europe. In recent years, increasing attention has been devoted to their ecological restoration, both to mitigate environmental impacts and preserve their essential functions.

Mires are divided into three sub-groups under the Habitats Directive. For the purposes of this guide, however, they are treated as a single group comprising 12 habitat types, 7 of which are Priority Habitats under Annex I of the Habitats Directive. This approach reflects the fact that mire types are primarily classified according to water source, which influences water and nutrient chemistry, and that different mire types often occur in complexes, making strict separation difficult. Nevertheless, we also provide specific information for each individual habitat type where relevant. The exceptional diversity of peatlands results from interacting factors such as hydrology, climate, geology, nutrient availability, vegetation, and land use (Joosten et al., 2017). This guidance provides a structured framework for their ecological characterization, identifying the key features and variables needed to assess habitat condition. In line with Article 17 of the Habitats Directive, which obliges Member States to monitor and report on the conservation status of natural habitats (including Annex I peatland types), this document supports the assessment of the 'structure and functions (including typical species)' parameter. The aim is to ensure consistency and comparability in habitat quality evaluation.

Across the EU, more than 30 methodologies from 18 Member States have been analysed to gain an overview of the approaches used to assess mire habitats. These range from single-habitat approaches (e.g., Poland) to broader methods covering mire groups (e.g., Spain, Ireland). Most methodologies focus on biotic variables, particularly species composition and indicator species. Functional variables, such as drainage impact, are also commonly assessed, while structural variables typically focus on vertical vegetation layers; horizontal structure and microtopography are rarely considered. Due to cost and complexity, most countries rely on qualitative or semi-quantitative assessments, often inferring hydrological and chemical conditions from species data. Among chemical variables, pH is the most widely measured.

Although field survey is the principal method employed by most Member States to collect habitat data, the field monitoring procedures are not standardized and are typically left to each country's discretion - making cross-country comparisons difficult. Nevertheless, a majority of countries share common assumptions, with periodic field assessment of selected indicators for structure and function forming the core of habitat monitoring.

In many cases, the same aspects of habitat quality are being measured, but different variables are used, making them not directly comparable. We interpreted the variables applied in each country and aligned them with the concepts and terminology defined in the framework for the ecological characterisation of mire habitats, which is developed in the first part of this document.

Thresholds for mire habitats vary across national methodologies. In some countries, data are still insufficient or criteria are still under development. Many approaches rely on expert judgment rather than precise measurements, even for quantitative variables. Some methodologies use broad concepts, such as habitat degradation, instead of clearly defined metrics, while others apply ordinal scales that do not explicitly indicate good or bad conditions. At the European level, documentation remains limited, and significant differences exist among Member States, even for the same habitat type. Much of the available data is based on vascular plant composition, with abiotic factors often considered indirectly.

Countries such as Spain, Poland, and Ireland apply distinct aggregation methods specifically for mire habitat types, while most Member States use a common procedure for all habitats or habitat groups. At the biogeographical scale, most Member States follow the Article 17 reporting guidelines. Some countries apply the “one-out, all-out” approach, whereby a mire habitat is considered to be in favourable condition only if all key criteria are met at every assessed location. Others use indices or descriptive statistics to aggregate data at broader spatial scales.

The number of sample plots per habitat type and the methods used for their selection vary across Member States. Most countries apply a systematic approach based on habitat distribution, size, and characteristics, with sample numbers determined by the frequency of the habitat. Selection methods include the use of expert knowledge or stratified sampling, taking into account geographical distribution, habitat variation, and conservation status. Monitoring sites range from undisturbed to disturbed areas, and often include permanent plots located both within and outside the Natura 2000 network, in line with standard assessment schemes.

Most Member States use sample-based monitoring schemes that rely on field mapping of individual habitat occurrences. These schemes differ in the number and size of plots, as well as in sampling design. The use of remote sensing remains limited. Sweden, however, has an established monitoring programme for all open wetlands that incorporates remote sensing. It also cooperates with Finland and Norway on the monitoring of palsa mires, using a method that combines aerial image interpretation and field surveys.

The final part of the document focuses on harmonising methodologies to ensure consistent data collection and assessment criteria across EU Member States, thereby enabling accurate comparisons and supporting mire conservation and restoration efforts. Despite the ecological importance of mires and the recognised need for their monitoring, Member States currently apply a wide range of variables, metrics, and methodologies. To harmonise mire condition assessments, a set of key principles should guide the selection of variables:

- Ensure ecological relevance to specific mire habitats.
- Prioritise sensitivity to environmental changes and management impacts.
- Use standardised methods for data collection and analysis to enable comparability.
- Adopt common metrics and units to facilitate integration across regions.
- Monitor at appropriate spatial and temporal scales.
- Ensure feasibility within available resources.
- Apply consistent methods to support long-term trend analysis.
- Guarantee equivalent assessments of habitat condition across Member States, while accounting for biogeographical, historical, cultural, and socio-economic factors.

Following these principles, a preliminary set of abiotic, biotic, and landscape variables is proposed, based on habitat characteristics, national assessments, and relevant literature.

We propose a set of variables for mire monitoring, categorized into abiotic (e.g., water table level, peat decomposition, pH, electrical conductivity), biotic (e.g., species composition, indicator species), structural (e.g., cover of plant functional types, microtopography), functional (e.g., disturbances as drainage, fire, erosion etc.), and landscape metrics (e.g., mire area, connectivity, fragmentation). The integration of traditional fieldwork with advanced technologies, such as remote sensing, open-access databases, and geospatial modelling, ensures robust, scalable, and comparable assessments across different regions and habitats. These methods not only provide detailed insights into habitat condition but also support adaptive management strategies aligned with conservation goals under the Habitats Directive and related EU policies.

This document has provided an analysis of the methodologies used for mire habitat monitoring across EU Member States, outlined the main ecological characteristics of mires, and proposed a framework for the harmonisation of habitat monitoring at the EU level. Although the proposed methodology is grounded in extensive information and draws on national experiences documented in habitat monitoring manuals, it is not intended to be definitive or prescriptive. Its feasibility and relevance must be evaluated within the context of different Member States and their specific ecological conditions and monitoring practices.

# 1. Definition and ecological characterisation

## 1.1 Definition and interpretation of habitats covered

Peatlands, or mires (actively forming peatlands), are peat forming wetlands commonly subdivided into **bogs** and **fens**, based on their water supply and typical vegetation. Bogs receive water and nutrients solely from atmospheric precipitation, whereas fens also receive water that has been in contact with mineral soil or bedrock. Due to this difference in water supply, bogs are strongly acidic and nutrient poor, while fens tend to be more nutrient-rich and may range from weakly acidic to alkaline. Some fens receive groundwater that is both acidic and nutrient-poor. Based on landscape position and water source, such transitional mires function like fens but have vegetation and hydrochemistry similar to bogs (Convention on Wetlands, 2021). The majority of peatlands in Europe are fens (Tanneberger et al., 2021). Mires are generally open landscapes dominated by mosses, graminoids, and low shrubs, but they may also include scattered small trees, especially along edges or in transitional zones. Information on wooded mires is provided under the group of forest habitats.

Group 7 - Raised bogs, Mires and Fens – as defined in the Interpretation Manual of European Union Habitats (European Commission, 2013), refers to mire-related open landscapes and is subdivided into three sub-groups:

- *Sphagnum* acid bogs – habitats 7110*, 7120, 7130*, 7140, 7150, 7160
- Calcareous fens – habitats 7210*, 7220*, 7230, 7240*
- Boreal mires – habitats 7310*,7320*

For the purposes of this guide, we have not subdivided the mires into these subgroups but treat them as a single group. This is because mires are typically classified based on their water source, which also governs water and nutrient chemistry. Individual mire habitats often occur in complexes with other mire habitat types, making strict separation difficult.

Mires are represented by 12 habitat types, seven of which are listed as a Priority Habitat in Annex I of the Habitats Directive. These habitats have some specific characteristics and aspects that should be taken into account, as described below (European Commission, 2013). We also present the corresponding EUNIS habitat types (Level 3), according to the EUNIS terrestrial habitat classification (EUNIS, 2021; Chytrý et al., 2020):

**7110*  Active raised bogs** (EUNIS, 2021: Q11 Raised bogs, Q13 Ombotrophic percolation mire). Acidic, ombrotrophic bogs, poor in mineral nutrients, sustained mainly by rainwater. The water level is generally higher than the surrounding water table. These bogs support perennial vegetation dominated by colourful *Sphagnum* hummocks, which allow the growth and maintenance of the bog system.

**7120  Degraded raised bogs** (EUNIS, 2021: Q11 Raised bogs), still capable of natural regeneration. These are raised bogs where the natural hydrology of the peat body has been disrupted, usually due to anthropogenic impacts, leading to surface desiccation and/or species change or loss. Sites are considered capable of natural regeneration if their hydrology can be restored and, with appropriate rehabilitation management, there is a reasonable expectation of re-establishing peat-forming vegetation within 30 years.

**7130*  Blanket bogs (*if active bog)** (EUNIS, 2021: Q12 Blanket bogs, Q22 Poor fen, Q24 Intermediate fen and soft-water spring mire). Extensive bog communities or landscapes found on flat or sloping ground with poor surface drainage, typically in oceanic climates with high rainfall. Although there is some lateral water flow, blanket bogs are mostly ombrotrophic.

*Sphagnum* mosses play an important role in all blanket bogs, but the cyperaceous component is more prominent than in raised bogs. Only active bogs qualify for priority status. The term "active" refers to sites still supporting a significant area of vegetation that is normally peat forming.

**7140 Transition mires and quaking bogs** (EUNIS, 2021: Q13 Ombotrophic percolation mire, Q21 Oceanic valley mire, Q22 Poor fen, Q23 Relict mire of Mediterranean mountains, Q24 Intermediate fen and soft-water spring mire, Q25 Non-calcareous quaking mire). Peat-forming communities that develop at oligotrophic to mesotrophic water surfaces, with characteristics intermediate between soligenous and ombrogenous types. They support a large and diverse range of plant communities. In extensive peaty systems, the most prominent vegetation types include swaying swards, floating carpets, and quaking mires formed by medium-sized or small sedges, typically associated with *Sphagnum* or brown mosses.

**7150 Depressions on peat substrates of the *Rhynchosporion*** (EUNIS, 2021: Q21 Oceanic valley mire, Q22 Poor fen, Q24 Intermediate fen and soft-water spring mire). These are highly constant pioneer communities of humid, exposed peat or, occasionally, sand. They typically form on stripped areas of blanket bogs or raised bogs, but can also occur on naturally seepage- or frost-eroded surfaces of wet heaths and bogs, in flushes, or within the fluctuation zones of oligotrophic pools with sandy, slightly peaty substrata.

**7160 Fennoscandian mineral-rich springs and spring fens** (EUNIS, 2021: Q24 Intermediate fen and soft-water spring mire). These habitats are characterised by a continuous flow of groundwater. In spring fens, water seeps upwards through the ground and the accumulated peat, creating favourable conditions for the growth of specialized vegetation.

**7210* Calcareous fens with *Cladium* mariscus and species of the *Caricion davallianae*** (EUNIS, 2021: Q43 Tall-sedge base-rich fen). This habitat is characterized by *Cladium mariscus* beds in the emergent-plant zones of lakes, on fallow land, or at successional stages of extensively farmed wet meadows adjacent to rich fen vegetation.

**7220* Petrifying springs with tufa formation (*Cratoneurion*)** (EUNIS, 2021: Q416 Hard water spring mires). Hard-water springs with active formation of travertine or tufa. These formations occur in a variety of environments, including forests and open countryside. They are generally small (point or linear formations) and dominated by bryophytes, particularly the *Cratoneurion commutati* community.

**7230 Alkaline fens** (EUNIS, 2021: Q41 Alkaline, calcareous, carbonate-rich small-sedge spring fen, Q42 Extremely rich moss-sedge fen, Q44 Calcareous quaking mire, Q46 Carpathian travertine fen with halophytes). Wetlands predominantly occupied by peat- or tufa-forming small sedge and brown moss communities. These develop on soils that are permanently waterlogged, with a soligenous or topogenous water supply that is base-rich and often calcareous. The water table typically lies at, just above, or just below the soil surface.

**7240* Alpine pioneer formations of the *Caricion bicoloris-atrofuscae*** (EUNIS, 2021: Q45 Arctic-alpine rich fen). Fens colonising neutral to slightly acidic gravelly, sandy, stony, sometimes mildly argillaceous or peaty substrates soaked by cold water. They occur on moraines, along spring edges, rivulets, and glacial torrents in alpine or subalpine zones, or on alluvial sands of pure, cold, slow-flowing rivers and calm backwaters. Permanent or prolonged soil frost is essential for the persistence of this habitat type. The low vegetation is composed primarily of *Carex* and *Juncus* species.

**7310* Aapa mires** (EUNIS, 2021: Q22 Soligenous mire). Mire complexes found in the southern, middle, and northern boreal zones characterised by minerotrophic fen vegetation in their central parts. Hydrotopographical mire units include: mixed mires, string fens, flark fens, unraised *Sphagnum fuscum* bogs, and unpatterned topogenous or soligenous lawn, carpet, or mud-bottom fens. Poor *Sphagnum* fens are the most common vegetation types, while brown moss fens may be frequent in some regions.

**7320* Palsa mires** (EUNIS, 2021: Q31 Palsa mires). Mire complexes located in northern boreal, orohemiarctic, and alpine regions, with a slightly continental climate, where the mean annual temperature is below -1°. These mires are mainly minerotrophic, except for the palsas – peat mounds containing sporadic permafrost. Palsas are usually 2-4 metres high, although examples up to 7 metres have been recorded in Finland and Sweden.

Temperature, precipitation and oceanity influence the distribution and variability of peatland types in Europe. The following mire regions, located within EU Member States, differ substantially in size, mire diversity, peatland condition and protection status (Tanneberger et al., 2021):

- The palsa mire region covers large areas in northern Finland and Sweden.
- The northern fen region (aapa mire region) covers large areas in the boreal vegetation zones in Sweden and Finland.
- The typical raised bog region is found in Fennoscandia and the Baltic states, with small exclaves in mountainous areas north of the Alps.
- The Atlantic bog region is located along the oceanic coast of western Europe, from Azores (Portugal) to Ireland. It is characterised by Atlantic raised bogs and blanket bogs.
- The continental fen and bog region lies in eastern Poland and is characterised by mosaics of fens and bogs.
- The nemoral-sub-meridional fen region includes large parts of France, Germany, and other Central European countries. Flat fen is the most characteristic mire type, although plane bogs and percolation fens also occur.
- The southern European marsh region includes wetlands across southern Europe, covering Iberian Peninsula and areas around the Mediterranean and Black Seas. These peatlands often have only a thin peat layer.
- The central and southern European mountain compound region relates to the vertical distribution of mire types. Flat fens and percolation fens are most common, but sloping fens and bogs also occur.

The EU Member State with the highest proportion of peatlands is Finland, where peat covers around 25 % of the land surface. Peatlands also cover approximately 20 % of Ireland and Estonia, and 15% of Sweden (Peatland Atlas, 2023).

## 1.2 Environmental and ecological characterisation and selection of variables to measure habitat condition

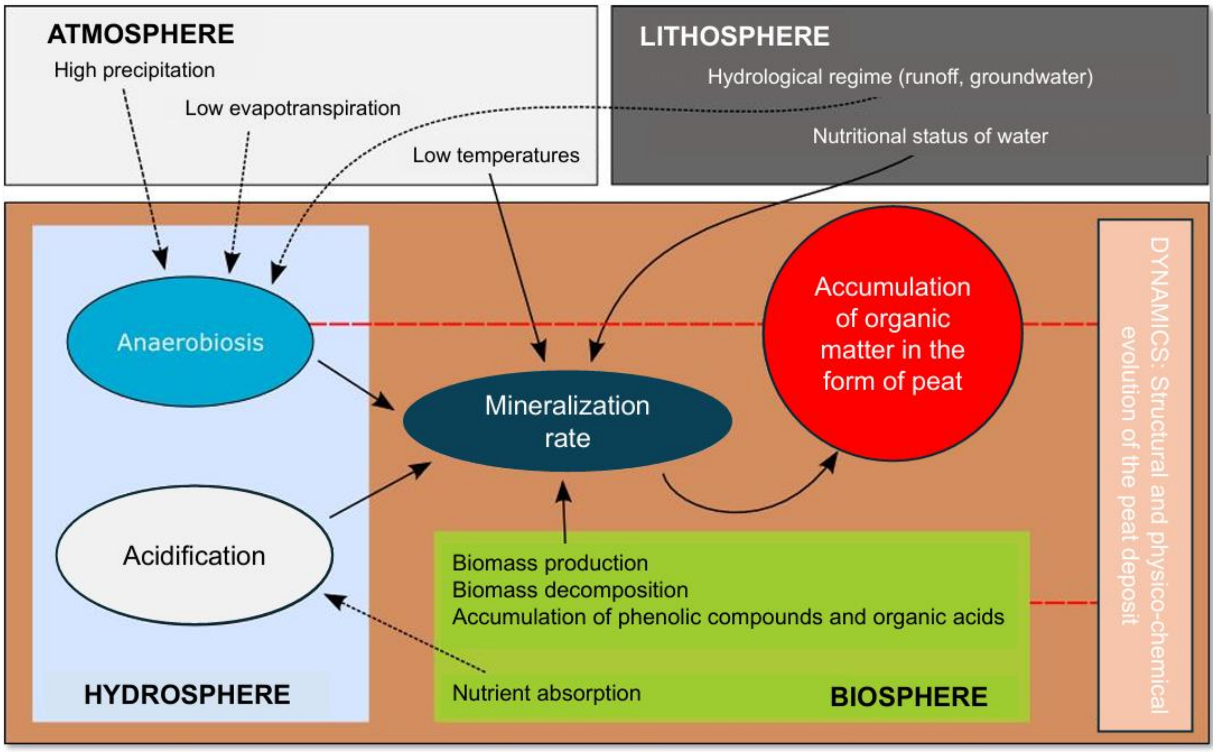
### 1.2.1 Ecological characterisation of peatlands

A peatland is an area with a naturally accumulated peat layer at the surface to a depth of at least 30 cm. This definition may include drained or dry peatlands. A mire is a peatland with vegetation that actively forms peat. A peatland in which peat accumulation has ceased (e.g., as a result of drainage) is no longer considered a mire. Peat is a material that has accumulated in situ (sedentarily) and consists of at least 30% (dry mass) dead organic material (Joosten et al., 2017).

A natural peatland is a wetland ecosystem in which organic matter production exceeds decomposition. Peat soil is formed from partially decayed material, which builds up slowly over thousands of years. Under conditions of near-permanent water saturation and oxygen deficiency, dead plants and mosses accumulate as peat (Figure 1).

In Europe, more than half of all pristine peatlands have been lost or converted, and only a few remain in good ecological condition. Peatland degradation continues today (European Union, 2020). The fact that degraded peatlands are a source of greenhouse gases is receiving increasing attention in the context of global warming (Joosten et al., 2016). Significant efforts are now being undertaken for their protection, conservation, and restoration. The EU Biodiversity Strategy for 2030 and Nature Restoration Law emphasise the restoration and strict protection of peatlands. The EU 2030 Climate and Energy Framework highlights that forests, agricultural land and wetlands (including peatlands) will play a central role in achieving the goals of the Paris Agreement. Under this framework, since 2021, all EU Member States are required to report on greenhouse gas emissions and removals from wetlands (European Parliament, 2018).

**Figure 1. Diagram of the biophysical control factors involved in the formation and accumulation of peat**




The interdependent relationships between the terrestrial subsystems (biosphere, hydrosphere, atmosphere and lithosphere) involved in peat formation and accumulation are summarized.
*Source*: Martínez-Cortizas & Silva-Sánchez (2019)
© Ministerio para la Transición Ecológica, Spain (2019)

Most ecological and floristic variation within mire vegetation is explained by three primary ecological gradients: **the acidity gradient**, ranging from acidic, base-poor to neutral, base- and bicarbonate-rich conditions; **the fertility gradient**, related to the availability of limiting nutrient elements, particularly nitrogen (N) and phosphorus (P); and the **water level gradient**.

Land use is an important additional factor influencing mire ecosystems (Wheeler & Proctor, 2010). However, these gradients are complex, as multiple environmental factors often change in the same direction.

In mires, strong functional relationships exist between plants, peat and water. If one of these components changes, the others will eventually respond as well- leading to shifts in peat formation, biodiversity, greenhouse gas fluxes and other ecosystem services. These components, however, do not respond at the same rate. In general, organisms are more readily affected than hydrology, and hydrology is more easily altered than the peat layer (Convention on Wetlands, 2021).

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

The description of key characteristics and corresponding variables used to assess mire condition (Table 4) follows the SEEA Ecosystem Accounting framework, adopted by the UN Statistical Commission as the global standard for ecosystem accounts (United Nations, 2021). Some of the variables described below are contextual or descriptive, serving to support understanding of the ecological functioning of mire habitats.

An adequate ecological characterisation of mires requires the quantification of parameters that provide information on the structure and functions of the habitat, as well as those that reflect external pressures. Internal factors include peat properties (e.g., density, ash content, elemental composition), water properties (e.g., acidity, ionic composition, dissolved organic carbon), and biological characteristics such as species composition. Among the external factors, it is necessary to asses both the direct impacts on peatlands – such as artificial drainage, livestock load, fertilisation and fires – and the indirect effects, such as air pollution, climate change, modifications of the hydrological regime of the basin, contamination of surface waters, and soil erosion and pollution (Martinez-Cortizas & García-Rodeja, 2009).

#### Abiotic characteristics

Abiotic characteristics describe the physical and chemical status of the habitat. All mires share many ecological functions and features due to similar ecohydrological processes, which are driven by permanent water saturation and the accumulation of organic matter as peat (Parish et al., 2008).

#### Physical state characteristics

As with all wetlands, mires are an integral part of the hydrological cycle, with water balance components including precipitation, total evaporation, surface flows and groundwater flows (Ingram, 1983). The most important physical status characteristics of mires include:

**Source of water**. Mires are commonly recognized as falling into two types based on the origin of their water supply. Ombrotrophic bogs are fed exclusively by direct precipitation in their central parts, whereas minerotrophic fens receive at least some water that has passed through mineral soil. In bogs, the upper peat layer lies above the water table of the surrounding mineral soil, meaning that all water and nutrients available to plants are derived from precipitation. For this reason, they are also referred to as ombrotrophic (ombrogenous) mires.

Fens are minerotrophic (geogenous) mires. Following the suggestion of Joosten & Clarke (2002), the classification focuses on the source of the water rather than on the genesis of the peatland. Based on this approach, geogenous mires are subdivided into the following types:

- **Soligenous** – fed by precipitation and near-surface runoff;
- **Lithogenous** – fed by groundwater, including limnogenous types influenced by water from rivers and lakes; and
- **Thalassogenous** – fed by seawater.

It is important to note that these terms refer solely to the origin of the water, not to its chemical quality. Geogenous water or minerotrophic mires are not necessarily rich in minerals, and ombrogenous water is not necessarily poor in them (Joosten et al., 2017).

**The hydrogenetic mire typology** describes the functioning of natural mires in terms of how water supply and water table fluctuations influence peat accumulation. Two main groups are distinguished: horizontal and inclining mires (Table 1).

### Table 1. Main groups of hydrogenetic mire types

| Main groups | Main hydrogenetic mire types | Typical hydrological restoration challenges |
|---|---|---|
| **A mire with a horizontal water table and either no lateral water flow or water that alternately moves in both directions along its slope**<br><br>**Horizontal mire** | Mire developing in or over an open water body<br>→ **Terrestrialisation mire** | Recreate open water habitats for early successional stages once peat has filled the entire water basin. |
| | Mire developing as result of a rising water table<br>→ **Water rise mire** | Raise the water table above the peat surface, to re-establish anoxic conditions, and maintain it at a high level over the long term. |
| | Mire developing through regular flooding by rivers (seasonal), lakes (wind-driven) or seas (lunar tides)<br>→ **Floodwater mire** | Restore regular flooding at progressively higher levels. |
| **A mire with an inclining water table and water flowing in a single direction along its slope(s)**<br><br>**Inclining mire** | Uppermost and deeper peat are porous, with water flowing through a major part of the peat body<br>→ **Percolation mire** | Remove degraded (low-permeability) peat layers or reintroduce an extremely regular and abundant water supply to support long term formation of new, highly permeable peat. |
| | Uppermost peat is compact, with water flowing mainly over the surface of the peat body. May occur on rather steep slopes<br>→ **Surface flow mire** | Halt peat erosion by re-establishing protective vegetation cover and dispersing water flow. |
| | The uppermost peat or vegetation has a conspicuous and effective vertical gradient in porosity. Water flows mainly between distinct V-notch-shaped surface structures of the peatland, or through the uppermost part of the coherent *Sphagnum* vegetation or peat body<br>→ **Acrotelm mire** | Support the development of a new V-notch-like structure: a surface layer with a pronounced vertical gradient in hydraulic conductivity and high-water storage capacity, both within the long-term average amplitude range of water table fluctuations. |

*Source*: Hans Joosten, Convention on Wetlands, 2021.

**Water level and water balance.** Water balance within a peatland depends on numerous flow and storage processes, both internal and external to the mire. It may include precipitation, surface stream inflow, groundwater exchange with underlying aquifers, seepage through peat, flow through pipes and fissures within the peat and adjacent substrata, diffuse flow over the peat surface, unconfined flow in directed channels, and evapotranspiration (Ivanov, 1981).

In undamaged mires, the water table is maintained close to the ground surface by groundwater, surface water inflow, or an excess of precipitation over evapotranspiration – resulting in a positive climatic water balance (Parish et al., 2008). Peat formation is possible where the water table remains near the surface for most of the time. In areas where the surface wetness is highly variable, or which are periodically flooded rather than continuously wet, soil aeration may prevent or delay the formation of peat (Rydin et al., 1999). A relatively stable water table is important to limit decomposition and to maintain suitable ecological conditions for peat-forming species. In boreal and temperate peatlands, for example, water levels 20 cm below the surface (or 10 cm above the surface) may lead to a negative carbon balance (Evens et al., 2021).

**Water temperature.** Water temperature is an important characteristic of groundwater systems, influencing both chemical and biological processes. In winter, groundwater temperature is usually higher than the air temperature, while in summer, when surface water temperature follows the average daily air temperature, groundwater temperature is noticeably lower. This makes water temperature a useful indicator for detecting groundwater discharge. In spring and autumn, there is a transitional period during which surface water and groundwater temperatures are close to the mean daily air temperature (Priede & Strazdiņa, 2022).

**Climatic conditions – air temperature and precipitation.** Peat development is typically associated with the cool, moist climates of the temperate and boreal zones, where persistent water saturation occurs (Clymo, 1983). In drier regions, the mechanisms that maintain waterlogged and anaerobic conditions – and thus enable peat accumulation – are more sensitive to the complexities of internal water storage, its redistribution via surface and groundwater flows, and variability in air temperature and precipitation. Elevated temperatures favour the decomposition of organic matter, and in such conditions higher precipitation is required to sustain significant peatland areas.

Mires are among the ecosystems most affected by climate change. Peatlands in the Northern Hemisphere are expected to become increasingly exposed to climate-related pressures. These include rising temperatures and shifts in the climatic water balance towards drier conditions, which are projected to cause water table drawdown and result in earlier and reduced spring floods (Heikkinen at al., 2023). Permafrost thaw, resulting from climate warming, threatens to release large amounts of carbon from high-latitude peatlands. The response of palsa peatlands to warmer conditions or altered snow dynamics has already been observed across northern Scandinavia (Valman et al., 2024).

**Peat decomposition.** The peat decomposition scale is used to estimate peat age, calculate accumulation rates, and understand hydrological and ecological conditions under which peat formation occurred. A wide range of methods are employed to reconstruct past climate based on peat stratigraphy. Among these, quantitative macrofossil and microfossil analyses, together with peat humification, are the most widely applied techniques (Borgman, 2006).

The physical properties of peat are closely linked to its botanical composition and degree of decomposition. As decomposition progresses, fresh plant material gradually transforms into amorphous humic matter. Several physical and chemical methods are available for determining the degree of decomposition. The most well-known of these is the von Post humification scale (von Post, 1922), which is widely used across various applications. The scale ranges from H1 (completely undecomposed plant material) to H10 (fully decomposed peat). Classification is based on the colour of peat moss, the fiber content and the colour of water squeezed from a sample.

More recently, a range of mostly alkaline extraction procedures have been developed to extract and quantify humic or fulvic acids from peat as indicators of decomposition (Biester et al., 2014). In addition, recent research has appled mid-infrared vibrational spectroscopy to asses peat decomposition (e.g., Martínez Cortizas et al., 2021). This technique is non-destructive, rapid, and requires only minimal amounts of dry, finely milled peat. However, these methods are more commonly used in research or detailed restoration monitoring rather than routine field surveys.

**Peat depth** reflects the extent of organic matter accumulation and is a key factor in estimating carbon stocks in peatlands. It can be measured manually using a peat corer or metal rod to determine the probable depth, or by employing ground-penetrating radar (FAO, 2020).

**Peat accumulation**. Various models and equations have been developed to assess the contribution of peatlands to the global carbon cycle (Clymo et al., 1998), and to understand the role of peat accumulation in regulating the global climate, particularly in the context of rising greenhouse gas levels (Charman, 2002). Clymo peat growth model describes peat accumulation as a two-layer system: the acrotelm (the upper, aerated layer of a living raised bog) and catotelm (the deeper, permanently water-saturated layers). The boundary between the relatively thin acrotelm and the catotelm – representing the bulk of the peat deposit – typically lies at the mean depth of the lowest water table (Table 2).

### Table 2. Main properties of the acrotelm and catotelm in peatlands

| Property | Acrotelm | Catotelm |
|---|---|---|
| **Water content and movement** | Variable; rapid movement | Constant; very slow movement |
| **Oxygen supply** | Aerobic (periodically) | Anaerobic |
| **Microbial activity** | High | Low |
| **Decay rate** | Rapid | Slow |

## Chemical state characteristics

The physical and chemical properties of soils are most relevant in the surface layer of the mire (to a depth of approximately 0.3 metres), where the majority of cultivated plant roots are located. These properties depend on several factors, including peat type, degree of peat decomposition, ash content, peat reaction (pH), peat fertility (nutrient content) and industrial contamination of the soil (e.g., heavy metals and persistent organic pollutants) (Joosten & Clark, 2002).

Among the most important chemical state characteristics of mires are **pH** and **base saturation**, which are the most frequently measured water chemistry variables and are closely related to the poor-rich vegetation continuum (also referred to as the poor-rich gradient). The pH of peatland waters is influenced by the production of acids during organic matter decomposition and the input of bases from groundwater or surface water. As a result, both pH and base saturation correlate with plant species composition (Joosten et al., 2017).

This chemical gradient spans from acidic bogs to calcareous, extremely rich fens. In this context, the term rich refer to mineral richness, and often - though not always - to a higher number of plant species. It does not necessarily indicate high nutrient availability. The poor-rich gradient can be divided as follows (Vitt & Chee, 1990; Rydin et al., 1999):

**Bogs**: pH generally <5.0; low alkalinity and low concentrations of base cations (Ca, Mg, Na, K)

**Fens**: pH generally >5.0; high alkalinity and base cation concentrations. Fens are further subdivided into:

- **Poor fens:** pH 4.5-5.5; low in base cations; little or no alkalinity.
- **Moderately rich fens:** slightly acidic to neutral (pH 5.5 - 7); low to moderate alkalinity.
- **Extremely rich fens:** pH above 7.0; high base cation concentration and high alkalinity.

**Electrical conductivity** (EC) measures the ability of water to carry an electrical current, which primarily depends on the concentration of dissolved ions. Because EC is highly sensitive to temperature, a temperature-compensated value – typically standardized to 25 ºC – is used for comparative purposes. This adjusted value is known as specific electrical conductivity (SEC) or specific conductance.

SEC can provide insight into the origin of the water. Rainwater, water in bogs, and recently infiltrated rainwater (young groundwater) typically exhibit low SEC values (10–250 µS/cm). In contrast, SEC values in groundwater from shallow aquifers generally range between 400 and 800 µS/cm, with median and average values of 550 and 650 µS/cm, respectively. Groundwater from deeper aquifers and seawater can show SEC values ranging from 1,000 to over 10,000 µS/cm. An unexpectedly high SEC in surface water or groundwater may indicate contamination (Priede & Strazdiņa, 2022).

In fens, water conductivity is also used as an indirect estimate of calcium content, as it primarily reflects the concentrations of $Ca_{2+}$ and $Mg_{2+}$ (Horsák, 2006).

**Nutrient availability.** Pristine mires are generally nutrient-poor environments. In such systems, the input of nutrients such as phosphorus and potassium is extremely low. In contrast, many peatlands – especially those affected by human activity - are highly nutrient-enriched due to peat mineralisation, fertilizer and manure application, and the input of airborne ammonia and nitrogen oxides from livestock, traffic and power plants (Lamers et al., 2015). Fens are particularly vulnerable to nutrient pollution (eutrophication), as they frequently occur in intensively managed landscapes. Nutrient enrichment can also result from flooding with nutrient- or sediment-rich surface water, as well as from the rewetting of previously drained or degraded mires.

The concepts oligotrophic, mesotrophic, and eutrophic have been formalised into a classification system using the nitrogen-to-carbon ratio in the soil (NC ratio, also expressed as C:N ratio). A higher C:N ratio indicates lower nitrogen availability. Alongside pH, the NC ratio is used to delineate mire types in vegetation classification. The soil C:N ratio serves as a proxy for nutrient availability (Joosten et al., 2017), based on the observed residual enrichment of nitrogen relative to carbon during the mineralization of organic matter. In more decomposed peat, this typically results in lower C:N ratio.

Changes in C:N ratios are thought to reflect shifts in bog surface wetness and associated peat decomposition (Biester et al., 2014). However, this interpretation remains a subject of debate in peat research. Variations in the C:N ratio may also result from complex interactions involving peat decomposition (influenced by hydrology and microbial activity), changes in vegetation (the source of organic matter), and atmospheric nitrogen deposition, among other factors (Hansson et al., 2013).

**Bulk density** (BD) refers to the dry weight of peat per unit volume (g $cm^{-3}$) and is commonly used as a simple proxy for the degree of total peat decomposition. Bulk density is influenced by moisture content: the higher the moisture content, the lower the bulk density (Chambers et al., 2011). As a result, peat has a lower bulk density than mineral soils.

Peat samples for bulk density and carbon content analysis can be collected at different depths, often simultaneously with the peat thickness measurements, and later analysed in the laboratory (FAO, 2020). Bulk density is a key variable for calculating elemental stocks in peat, such as carbon accumulation and total carbon stocks. This is particularly important in calcareous mires, where a portion of the total carbon is present as inorganic carbon.

**Acidification** of the minerotrophic mire habitats. Sulphur can influence the pH of mires, contributing to acidification. While this may occur as part of autogenic peatland processes, it is often exacerbated by human activities and their consequences, such as acid rain, air pollution, fertilizer use, artificial drainage and eutrophication. Acidification is linked to the gradual loss of contact with mineral-rich water as peat accumulates above the water table. This leads to ecological succession from rich fen to poor fen (Lamers et al., 2015). Two main factors are involved in this process: the physical shrinking of open spaces in fen habitats, often due to the expansion of more competitive *Sphagnum* species, and a shift towards more acidic conditions (Hájek et al., 2022).

### Biotic characteristics

#### Compositional state characteristics

Mires - especially bogs - typically exhibit low species diversity, but a high occurrence of unique species, a broad range of morphological forms, and considerable diversity of ecosystem types across spatial scales.  This diversity reflects a combination of geomorphological variation and climatic zonation (e.g., Pfadenhauer et al., 1993). Vegetation composition has long played a central role in mire classification, as it serves as an effective indicator of at least three key ecological factors relevant to land use: base-richness, nutrient availability, and moisture conditions (Wheeler & Proctor, 2000).

**Species composition and typical species.** Mires support numerous specialist species adapted to specific environmental conditions. Species diversity patterns in these habitats are closely tied to environmental gradients. As a result, the composition of typical (frequently occur in a given habitat, reflect its structure and function, and are often used in conservation assessments such as Article 17 reporting) and diagnostic (species whose presence helps define or identify a particular habitat type, they are largely restricted to it) species can vary considerably between European regions - even within the same habitat type.

**Indicator species** in mire ecosystems are often classified as either positive or negative indicators based on their presence, abundance, and the environmental conditions they signify. Positive indicator species are associated with healthy, undisturbed mire conditions, while negative indicator species suggest disturbance, degradation, or unfavourable environmental changes. Monitoring indicator species is a fast, cost-effective, and non-destructive method for assessing habitat condition.

**Indicator values** for vascular plants (Ellenberg et al., 1991) are widely used in ecological research as proxy measure of environmental conditions, eliminating the need for direct physical measurements. These values – which have recently been extended to cover a large portion of the European flora (Dengler et al., 2023; Tichý et al., 2023) - provide species-level indicators for factors such as light, temperature, moisture, soil reaction, nutrients and salinity. Further, work by Midolo et al. (2023) introduced indicator values for disturbance frequency, disturbance intensity, grazing pressure, mowing frequency and soil disturbance. These values can be used to identify species expanding within a habitat that exhibit uncharacteristically high or low values for that habitat type. Alternatively, the mean indicator values across all species at a site can be calculated at two time points (e.g., t1 and t2) to monitor ecological change over time.

Hájek et al. (2020) published an updated indicator system for soil moisture and water table depth in European mires and associated grasslands. This system extends the Ellenberg-like Ecological Indicator Values (EIVs) and uses a scale from 1 to 12 to represent each species' moisture optimum. In addition to species optima, the system includes ecological valences which indicate the minimum value (drought intolerance), the maximum value (flooding tolerance), and the range of values (tolerance breadth). The updated EIV system developed by Hájek et al. (2020) was based on species co-occurrence data and constructed using a combination of statistical and expert-based approaches. A complementary list of Ellenberg indicator values for 1,068 Central European bryophytes was published by Simmel et al. (2020).

### Structural state characteristics

**Plant functional types.** Plants in peatlands can generally be grouped into five main plant functional types (Walker et al., 2015): a) Mosses with *Sphagnum* species dominant in bogs and poor fens, and brown mosses dominant in alkaline fens; b) Graminoids – including grasses (Poaceae), sedges (Cyperaceae) and rushes (Juncaceae); c) Forbs – broadleaf herbaceous plants and pteridophytes; d) Shrubs – subdivided into evergreen and deciduous species; and e) Trees.

Most open peatlands are characterized by a vegetation cover dominated by mosses, graminoids, and low shrubs. When disturbed, the most apparent changes include an increase in tree layer species, a denser canopy cover, and a rise in the average height of the tree layer (Paal et al., 2016).

**Microrelief structures.** The surface of most mires is uneven, and vegetation composition varies across microrelief features in response to moisture gradients, water table fluctuations, and peat firmness (Joosten et al., 2017). Bogs, in particular, exhibit pronounced small-scale topographic complexity, often including bog pools, hollows, hummocks, ridges, and a lagg zone, which follow a gradient of water level variation. These micro-topographical formations support distinct vegetation communities; each adapted to specific moisture conditions (Korpela et al., 2020). The hummock–hollow complex is a dominant feature in many peatlands and plays a significant role in ecological, hydrological, and biogeochemical processes including carbon dynamics (Graham et al., 2020).

Aapa mires exhibit a distinct microtopography, characterized by elevated strings alternating with lower, wetter flarks. These patterned features are typically oriented perpendicularly to the slope of the mire surface. Unlike the hummocks and hollows found in raised bogs, however, they do not form rim-like structures.

Palsa mires are defined by the presence of palsas - raised peat mounds containing permafrost cores. These cores are composed of frozen peat or silt, interspersed with thin layers of ice and small ice crystals. Surrounding the taller palsas are pounus - smaller, lower peat hummocks (less than 50 cm in height) with non-permanently frozen cores (Seppä, 2002).

**Tufa formation** is the most important precondition for the existence of the habitat type 7220* (Petrifying springs with tufa formation), and it requires active spring processes and ongoing calcium carbonate deposition. Typically, calcium carbonate precipitates as small particles that encrust dead plant material and/or form solid calcareous rock (Priede, 2017). Tufa formation occurs within a pH range of 6.9 to 9.0, with a mean around pH 8. This process is characteristic of several habitat types, including 7220*, 7210* and 7230. Alkaline fens, which are fed by calcareous groundwater, often include zones of active surface tufa deposition, particularly in Central Europe (Grootjans et al., 2021).

### Functional state characteristics

Human activities have significantly affected the functioning of mires, often leading to their degradation and the loss of essential ecosystem services.

**Drainage cover.** Drainage is one of the main causes of mire degradation and loss due to human intervention. When a mire is drained, peat formation ceases and is replaced by secondary pedogenetic processes such as mineralisation, humification, shrinkage and subsidence, consolidation, compaction, dislocation, leaching and the accumulation of soil substances. These changes result in the development of hydrophobic topsoil, which greatly reduces the mire's water regulation and storage functions (Paal et al., 2016).

Drainage also leads to peat oxidation, a process in which dry, aerobic conditions intensify microbial activity and soil decomposition. This contributes to carbon dioxide emissions and often causes subsidence (loss of surface elevation). It can also trigger shifts in plant communities that fundamentally alter the carbon and water balance of the peatland (Loisel & Gallego-Sala, 2022). Drained peatlands are typically characterized by low groundwater levels and high seasonal fluctuations, leading to inconsistent water saturation, increased soil temperature and greater nutrient availability. LiDAR (Light Detection and Ranging) technology can be used to detect both the surface water level in drainage canals and the surrounding ground surface elevation, making it possible to determine the canal water depth below the land surface (FAO, 2020).

**Peat erosion.** Although peat erosion occurs naturally, it can be significantly accelerated by human land-use practices and climate change. Peat is highly susceptible to wind erosion when dry and loose, especially where the surface is bare. This is common in exposed uplands and in areas affected by peat extraction (Campbell et al., 2002). Rain splash and surface runoff can also cause erosion on bare peat. Drainage intensifies organic matter decomposition, increasing the leaching of nutrients and promoting both erosion and the weathering of drainage channels. The scale and the severity of erosion vary by peatland type and by the degree of degradation (Joosten et al., 2012).

**Peat extraction.** Large-scale peat extraction began in the late 19th century, initially for fuel and later for horticultural use. This form of peatland degradation continues to the present day and negatively affects the functioning of mires (European Union, 2020).

**Fires.** In mires, fires trigger succession changes in vegetation cover and lead to increases in soil temperature and nutrient availability. Fires occur across many peat-rich biomes and can severely damage peatland carbon stocks. Lowered water tables - resulting from past or present climate fluctuations, or human disturbance - increase both the frequency and extent of peat fires. Peat fires are typically dominated by smouldering combustion, a slow-burning process that can persist even under wet conditions (Goncharova et al., 2023).

**Mowing and grazing.** For decades, mowing has been a traditional management tool in European fens, while grazing has primarily been applied in bogs. However, bogs are particularly sensitive to overgrazing and trampling, and in recent decades, overstocking has negatively affected upland landscapes and biodiversity. At the same time, the cessation of traditional land use has caused fens to disappear rapidly from many landscapes. Mowing helps to control the spread of tall herbs, prevents encroachment by shrubs, and improves conditions for fen-specific species. However, effective suppression of expansive tall vegetation typically requires several consecutive years of mowing.

Moderate grazing disturbance can increase species diversity by creating microniches, such as areas of varying sward height and patches of trampled bare ground. However, intensive grazing can damage the soil, ground vegetation, and soil fauna - especially when cattle are used. In addition, grazing increases the nutrient content of the soil through dung deposition, particularly when livestock are additionally fed (Priede, 2017).

### Landscape characteristics

At the landscape scale, mires display distinctive features that set them apart from other ecosystems. These include their hydrology, topography, vegetation, soil properties, and ecological functions.

**Mire habitat area.** The area occupied by individual mires is critical for maintaining populations of rare and habitat-specialized species.

In mire ecology, a hierarchical **landscape-level classification** (Table 3) is used to describe spatial scales within a mire system. This provides a structured framework for understanding mire complexity and connectivity.

**Table 3. Elements of hierarchical mire classification (after Minayeva et al., 2017).**

| The landscape | Description | Vegetation unit |
|---|---|---|
| **Macrotope** | The mire complex (or system; several merged mire massifs). A macrotope refers to the entire mire system, often including multiple mesotopes. It represents the largest spatial unit in mire classification and is defined by its overall hydrology, topographical setting, and landscape position. | Biogeographic zone |
| **Mesotope** | The mire massif (separate raised bog, fen, etc.). A mesotope refers to a distinctive hydrological and geomorphological unit within a mire, eg., a bog dome within a raised bog. | Mire massif type |
| **Microtope** | Homogeneous element of landscape heterogeneity within the mire massif (hummock-hollow complex, margin, sedge mat, *Sphagnum* carpet). | Complex of phytocoenoses |
| **Microform (Nanotope)** | Hummock, hollow, pool, ridge. | Phytocoenosis |
| **Vegetation mosaic** | Microcoenosis, tussock, etc. | Microcoenosis |

**Landscape connectivity.** Due to their relative naturalness, preservation, and stability, peatlands play a key role in supporting landscape connectivity. Watershed and floodplain peatlands function as corridors and refuges for biological species. Peatlands located in intermediate positions within river basins provide functional connections across the landscape by enabling the flow of water, minerals and other substances, and contribute to the stabilisation of temperature regimes (Minayeva et al., 2017). Mires maintain relatively stable conditions - such as microclimate and water availability - and thus contribute to ecosystem connectivity by offering refuge for species (Minayeva & Sirin, 2012).

**Fragmentation**. Fragmentation can be caused by roads, drainage systems, and land use changes, leading to reduced species movement and impaired ecological functioning.

## Table 4. Framework for the ecological characterisation and selection of variables to assess mire habitat condition

| Ecological characteristics | Types | Description | Examples of associated variables |
|---|---|---|---|
| **Abiotic characteristics** | **Physical state characteristics** | **Source of water, water level, water balance**, including all inflow and loss components, as well as changes in water storage within the peat (e.g., water-table fluctuations).<br>**Temperature** of water, including mean and extreme values and seasonal oscillations. May serve as proxy for groundwater discharge.<br>**Climatic conditions** such as variability in air temperature and precipitation in relation to peat formation.<br>**Peat decomposition.** The slow decomposition in mires leads to peat accumulation and long-term carbon storage.<br>**Peat depth**, used for estimating carbon stocks and long-term accumulation in peatlands. | - Water table depth measurements (minimum, average, maximum)<br>- Groundwater discharge evidence<br>- Soil moisture (%)<br>- Soil/water temperature (mean, minimum, maximum)<br>- Air temperature<br>- Precipitation data from rain gauges and weather stations<br>- Degree of peat decomposition (e.g., Von Post scale, ash content as a proxy) – applicable mainly to bogs.<br>- Peat depth and volume |
| | **Chemical state characteristics** | **pH and base saturation**<br>**Electrical conductivity** reflecting the amount of dissolved ions in water. Indicates water source (and possible pollution); may be used as proxy for calcium richness.<br>**Soil nutrient availability**, including nitrogen and phosphorus content relevant to eutrophication.<br>**Acidification**, especially the impact of sulphur on mire pH in fens. | - Water/ soil pH value<br>- Peat water conductivity (μS $cm^{-2}$)<br>- Nutrient concentrations (N, P)<br>- Base cation concentrations (Ca, Mg, Na, K) in fens<br>- Alkalinity – concentrations of bicarbonate ($HCO^{3-}$) in fens<br>- Soil $N_C$ ratio<br>- Bulk density of soil (used to calculate total C in kg/$m^3$<br>- Dissolved organic carbon (DOC)<br>- Total dissolved solids (TDS)<br>- Redox potential (ORP)<br>- Sulphate concentrations |
| **Biotic characteristics** | **Compositional state characteristics** | **Species composition and typical species** occurring in local plant and animal communities.<br>**Indicator species**, including mosses, vascular plants, and invertebrates.<br>**Indicator values** for vascular plants. | - Species composition<br>- Number of habitat-specialist plant and animal species<br>- Presence of positive/ high quality indicator species<br>- Cover of negative indicators (e.g., competitive native herbs, dwarf shrubs)<br>- Species-level ecological indicator values |
| | **Structural state characteristics** | **Plant functional types**<br>**Microrelief structures** based on microtopography of mire<br>**Tufa formation** – precipitation of calcium carbonate | - Cover of mosses, graminoids, and low shrubs<br>- Microrelief structure of mire (e.g., hummock and lawn/carpet species cover)<br>- Tufa structure cover (e.g., terraces, ridges or mounds) |

| Ecological characteristics | Types | Description | Examples of associated variables |
|---|---|---|---|
| | **Functional state characteristics** | **Drainage cover**<br>**Disturbances** such as peat erosion, peat extraction, fires, etc.<br>**Mowing and grazing**, especially the intensity and frequency of these activities | - Evidence and cover of drainage structures and their functionality<br>- Slope and depth of drainage ditches<br>- Frequency and cover of disturbances (e.g., peat extraction, peat erosion, fire)<br>- Grazing pressure<br>- Mowing frequency |
| **Landscape characteristics** | | **Size of mire area** and size of mire complexes<br>**Habitat connectivity** - the degree of connectedness between individual mire patches<br>**Habitat fragmentation** | - Mire and mire complex area (in hectares)<br>- Presence of linear features that promote connectivity (e.g., corridors, water flows)<br>- Evidence of barriers (e.g., roads, land use changes) |

## 1.3 Selection of typical species for condition assessment

Typical species of the habitat are used to assess the habitat conservation status. The Habitats Directive uses the term ‘typical species’, but it does not give a definition for use in reporting.

For a habitat type to be considered in favourable conservation status, the Directive requires that both its structure functions and its ‘typical species’ are in a favourable status (Art. 1(e)). According to the guidelines for reporting under Article 17 (European Commission, 2023), typical species should be selected from those that occur regularly and with high constancy (i.e., are characteristic) within a habitat type, or at least within a major subtype or variant. They should include species that are good indicators of favourable habitat quality, e.g., by signalling the presence of a broader group of species with specific habitat requirements.

Typical species should also include those that are sensitive to changes in habitat condition - so called early warning indicator species. In addition, they should provide supplementary information beyond what is already captured through monitoring of the habitat’s structure and functions.

Typical species may be drawn from any taxonomic group. While vascular plants are the most frequently selected, attention should also be given to lichens, bryophytes, fungi, and animals. Among animals, both vertebrates – such as birds – and invertebrates should be considered. Many ecological functions, such as pollination and decomposition, rely mainly on invertebrates, and their exclusion may lead to incomplete assessments of habitat function.

Plant species play a key role in defining the function, and in the characterisation and assessment of habitats. They are widely used in biodiversity monitoring because they provide insights into abiotic environmental conditions (e.g., Ellenberg et al., 2010).

The interpretation of mires – especially in terms of species indicators – varies widely at both international and regional levels. In their national habitat manuals, countries often define different species and varying numbers of indicator species (Joosten et al., 2017).

In discrete island-like ecosystems such as mires, it is helpful to distinguish between two groups: habitat specialists - species with high fidelity to the mire system, and matrix-derived species - species that also occupy adjacent habitats and can colonise mire patches from surrounding areas (Horsáková et al., 2018). In mires, bryophytes and vascular plants make up the majority of these habitat specialists and should therefore be considered essential in any assessment or monitoring.

**Habitat specialists – bryophytes.** Bryophytes serve as excellent ecological indicators and play a crucial role in mire formation as key components – or ecosystem engineers. They are essential to peatlands because they provide the organic material from which peat is formed. Most *Sphagnum* mosses thrive in acidic, permeable and nutrient-poor environments and dominate in bogs and poor fens. The composition of *Sphagnum* species in a site can provide valuable information about environmental conditions such as pH, calcium concentration, shad and water level (Rydin & Jeglum, 2013).

Unlike *Sphagnum*, rich fen-specialised bryophytes – commonly referred to as brown mosses due to their colour – do not produce significant acidity. With the influence of calcareous groundwater, these systems become quite alkaline (Vitt et al., 1995). Although bryophytes are often considered difficult to identify, they should be included in peatland monitoring due to their strong indicative value and functional importance.

**Habitat specialists – vascular plants.** Only very specific vascular plants are able to co-inhabit peatlands alongside mosses. The range of vascular plants occurring in peatlands is limited to highly specialised species or those with strong capacity to adapt to the extreme conditions of the habitat. These species occur within the target habitat but are typically rare or absent in other habitats. Their selection is habitat-specific, and lists of typical species are provided in national and regional habitat manuals.

**Animal species.** In general, animal taxa tend to be more demanding of habitat conditions than plants, particularly in terms of structural components and specific requirements for feeding, reproduction, and other life functions. They also tend to respond more rapidly to environmental changes.

Surrogate taxa are often selected to allow broader assumptions about the peatland status. A surrogate taxon should include a wide range of typical peatland species with well-known ecological traits and a demonstrated sensitivity to habitat change, typically reflected in shifts in abundance. Multi-taxon approaches for the ecological assessment of peatlands – researched and/or applied in various contexts – have included combinations of birds, butterflies, orthopterans, ground beetles, dragonflies, ants, oribatid mites and spiders (in Hammerich et al., 2022).

Invertebrates can serve as effective early warning indicators due to their high reproductive rates and short life cycles, which allow them to respond quickly to environmental changes (Spitzer & Danks, 2006). Their use in monitoring the ecosystem health of peatlands is increasing across Europe. Useful bioindicator groups include Annelida, Arachnida, Acarina, Collembola, Odonata, aquatic Hemiptera, Lepidoptera, Tipulidae, Formicidae, various Coleoptera, and entire invertebrate assemblages (see Baltzer et al., 2016).

When selecting bioindicator groups, their geographic range should also be taken into account. A broad distribution is advantageous, as it allows for more universal application across different countries. Indicator species groups are used to assess the quality and ecological integrity of mires. These species are sensitive to environmental change and can provide insights into the status and functioning of mire ecosystems. The most effective indicator species groups for assessing mire quality are included in Table 5.

## Table 5. Selection of typical species for monitoring mire habitats

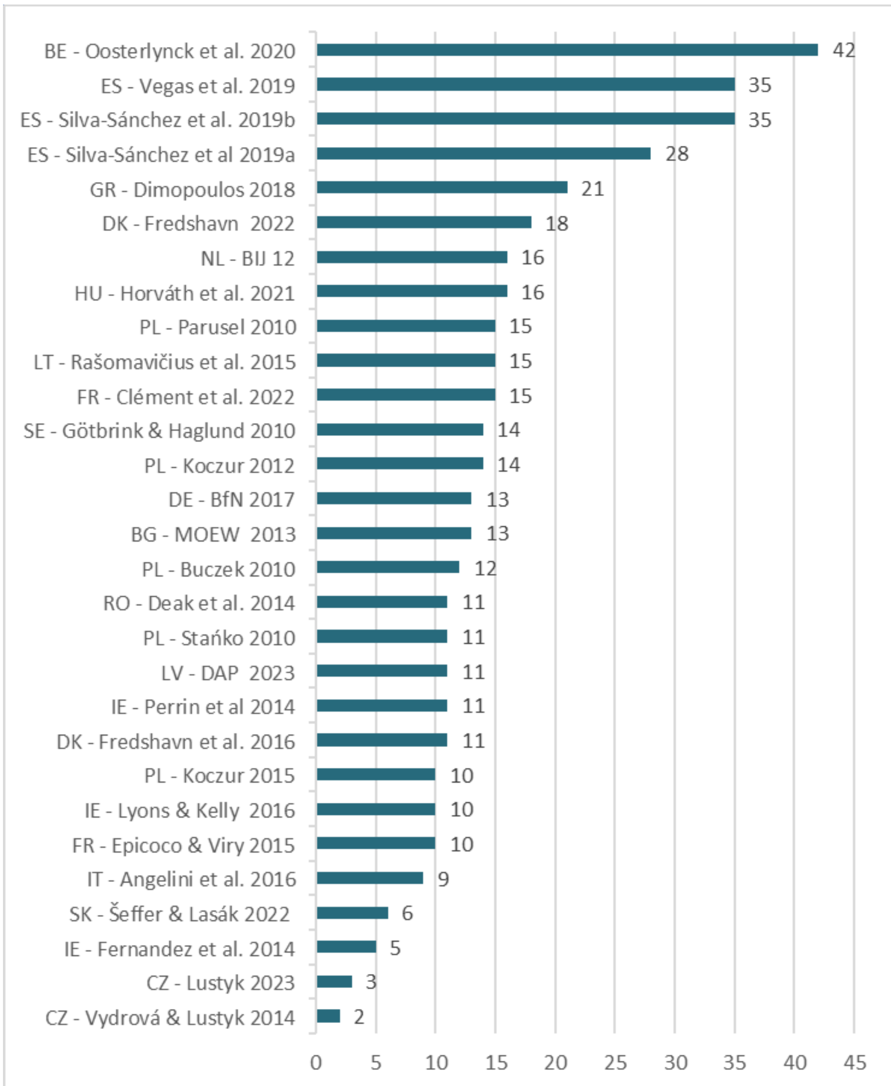
| Species Group | Ecological notes - Bioindication | Sensitive to Changes in Quality |
|---|---|---|
| ***Sphagnum* mosses** | *Sphagnum* species are crucial indicators due to their role in peat formation and water retention. Their presence, abundance, and condition provide information about environmental quality. | Different *Sphagnum* species respond rapidly to changes in moisture and nutrient availability. |
| **Brown mosses** | Brown mosses grow in less acidic, nutrient-rich, calcareous conditions typical of fens. They indicate stable, waterlogged environments. | Brown mosses are highly sensitive to changes in water chemistry, hydrology, and nutrient levels. |
| **Ericaceous shrubs** | Ericaceous shrubs are adapted to acidic, nutrient-poor, and often waterlogged conditions, typical of bogs and poor fens. | Some typical ericaceous species are highly sensitive to fluctuations in water levels, requiring stable soil moisture without prolonged drought or excessive flooding. |
| **Sedges and graminoids** | Sedges and graminoids can indicate nutrient levels, soil acidity or alkalinity, and the overall quality and stability of mire habitats. | Shifts in sedge and graminoid communities can reflect disturbance. A decline in sensitive species and a rise in tolerant ones may indicate habitat degradation. |
| **Molluscs** | Molluscs (e.g., snails) serve as indicators of high-quality fen habitats. | Molluscs are sensitive to hydrological conditions, water chemistry, and overall habitat quality, making them valuable for monitoring. |
| **Aquatic insects** | Aquatic insects (e.g., dragonflies, butterflies, beetles, spiders) reflect habitat diversity, water quality, and hydrological dynamics. | Aquatic insects are sensitive to water quality and hydrological change, and serve as indicators of mire health. |
| **Birds** | Birds are valuable bioindicators of mire health and quality due to their sensitivity to habitat changes. | Many bird species are sensitive to changes in habitat structure, water quality, and food availability. |
| **Amphibians and reptiles** | Amphibians and reptiles respond to changes in water quality, hydrology, and vegetation structure, making them useful indicators of mire condition. | Amphibians and reptiles respond to changes in water levels, habitat structure and disturbance, indicating the presence of suitable, undisturbed breeding and feeding habitats. |
| **Microbial communities** | Microbial communities (bacteria, archaea, fungi) play a key role in nutrient cycling and peat formation; their presence and composition can indicate ecological processes and environmental stability. | Microbial communities are sensitive to shifts in water chemistry, nutrient levels, pH, and hydrological conditions, reflecting changes in ecological functioning. |

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

The assessment and monitoring of habitat condition are critical components of biodiversity conservation, providing essential data for effective management and policy-making. We have analysed 29 methodologies for assessing and monitoring the condition of mire habitat types from 18 Member States (Figure 2). In addition, monitoring approaches based on remote sensing methods for palsa mires (priority habitat 7320*) and aapa mires (priority habitat 7310*) are also referenced in the text below, covering Sweden and Finland.

In total, 37 methodologies from 18 Member States have been reviewed (see Annex). These vary from habitat-specific methodologies, such as those developed in Poland for individual mire types, to broader approaches targeting mire formation groups, as seen in Spain and Ireland, and even to methodologies encompassing all non-forest habitats, including peatlands.

**Figure 2. Number of variables used in monitoring mires across the 29 methodologies analysed**




*Source*: Own elaboration

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

Most mire habitats share common characteristics and condition assessment variables; however, habitat 7220* Petrifying springs with tufa formation (*Cratoneurion*) exhibits some specific features which are outlined below.

The variables used across countries are based on partially overlapping, yet sometimes divergent, concepts and terminology. Although field survey is the principal method employed by most Member States to collect habitat data, the field monitoring procedures are not standardized and are typically left to each country's discretion - making cross-country comparisons difficult. Nevertheless, a majority of countries share common assumptions, with periodic field assessment of selected indicators for structure and function forming the core of habitat monitoring.

In many cases, the same aspects of habitat quality are being measured, but different variables are used, making them not directly comparable. We interpreted the variables applied in each country and aligned them with the concepts and terminology defined in the framework for the ecological characterisation of mire habitats (Table 4). The results are summarized in Table 6.

The analysis shows that most methodologies focus on compositional and structural biotic variables. Water regime – typical of the physical abiotic state of mires – and functional biotic variables are also frequently used. In contrast, chemical abiotic state variables and landscape variables are rarely included.

Metrics and measurement methods are precisely defined in some countries but less so in others. Exact measurements – such as water level fluctuations, pH, electrical conductivity, nutrient availability and other soil properties – are used in few countries. However, since collecting this information can be costly and labour-intensive due to the large number of surveyed plots, these characteristics are assessed indirectly in several countries, typically through qualitative evaluation based on species composition.

In the following section, we compare the key habitat characteristics defined in Section 1.2 with the variables used in national methodologies, and provide a more detailed evaluation.

*Active raised bogs (7110). © Jaroslav Košťál

**Table 6. Variables measured for mire habitats in national methodologies**

For some Member States, multiple variables were considered, as shown in Figure 2

| Ecological characteristics | BE | BG | CZ | DE | DK | ES | FR | GR | HU | IE | IT | LT | LV | NL | PL | RO | SE | SK |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1. Abiotic characteristics** | | | | | | | | | | | | | | | | | | |
| **1.1 Physical state characteristics** | | | | | | | | | | | | | | | | | | |
| **Water regime** | | | | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | | |
| **Peat decomposition** | | | | | | ■ | | | | | | | | | | | | |
| **1.2 Chemical state characteristics** | | | | | | | | | | | | | | | | | | |
| **pH** | | ■ | | | ■ | ■ | | | | ■ | ■ | ■ | | ■ | ■ | | | |
| **Electric conductivity** | | | | | | ■ | | | | | ■ | | | | | | | |
| **Nutrient availability** | | | | | ■ | ■ | | | | | ■ | | | ■ | | | | |
| **2. Biotic characteristics** | | | | | | | | | | | | | | | | | | |
| **2.1 Compositional state characteristics** | | | | | | | | | | | | | | | | | | |
| **Plant species composition and typical species** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Plant indicators** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Animal indicators** | | | | ■ | | | ■ | ■ | | | ■ | | | ■ | | | ■ | |

| Ecological characteristics | BE | BG | CZ | DE | DK | ES | FR | GR | HU | IE | IT | LT | LV | NL | PL | RO | SE | SK |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2 Structural state characteristics** | | | | | | | | | | | | | | | | | | |
| **Plant functional types** | | | | | | | | | | | | | | | | | | |
| **Microrelief structures** | | | | | | | | | | | | | | | | | | |
| **Tufa formation** | | | | | | | | | | | | | | | | | | |
| **2.3 Functional state characteristics** | | | | | | | | | | | | | | | | | | |
| **Drainage structures** | | | | | | | | | | | | | | | | | | |
| **Management evidence** | | | | | | | | | | | | | | | | | | |
| **Habitat degradation and disturbance** | | | | | | | | | | | | | | | | | | |
| 3. **Landscape/Seascape characteristics** | | | | | | | | | | | | | | | | | | |
| **Fragmentation** | | | | | | | | | | | | | | | | | | |
| **Habitat area** | | | | | | | | | | | | | | | | | | |

## Abiotic characteristics: variables, metrics and measurement methods

### Physical variables

**Hydrological conditions.** A high and stable water table close to the surface – indicative of active peat formation and maintenance of anaerobic conditions – is essential for mire ecosystems. Quantitative monitoring of the water balance through measurement of water table depth at different points during the growing season is implemented in countries such as Italy, typically using permanent piezometric tubes or portable instruments (Angelini et al., 2016).

On site visual expert assessment is also widely used as practical approach for evaluating mire condition (e.g., Germany – BfN, 2017, Hungary – Horváth et al., 2021, Greece – Dimopoulos, 2018). These expert assessments rely on the experience of field ecologists and hydrologists, who interpret visual indicators of mire health – such as the presence of standing water or a visible water table close to the surface – using simple tools like measuring rods or estimation techniques. In Poland, for instance, if piezometric measurements are not available, the depth of the groundwater table – or where relevant, surface water table – is estimated without specialised equipment at five locations spaced at 50 m intervals along a transect (three at relevé sites and two between them) (e.g., Koczur, 2012). In Netherlands, the percentage of the surface area with the average lowest groundwater level and average spring groundwater level is determined every six years (BIJ, 12).

However, visual expert assessments of the hydrological regime in mires may be limited due to their qualitative nature and may not provide sufficiently robust data. In Latvia, as in several other countries, water table measurements in mires have most often been carried out in the context of LIFE projects, typically aimed at achieving specific conservation goals within a defined territory and timeframe (Priede et al., 2019).

In Spain, monitoring of habitat 7220* includes the measurement of flow volume and regularity, water temperature and turbidity, as well as changes in annual precipitation and temperature (Vegas et al., 2019). Water flow is also measured for this habitat in Ireland (Perrin et al., 2014).

**Peat decomposition** is rarely measured or assessed, but it is included, for example, for bog habitats in Spain (Silva-Sánchez et al., 2019a). As peat accumulates, it typically exhibits low bulk density due to its high organic matter content. Decomposition of this organic matter over time can lead to increased bulk density. Ash content has also been proposed as a simple proxy for the degree of peat decomposition, particularly in acidic peatlands. Bulk density provides insights into the compaction of different peat horizons, while ash content reflects the proportion of mineral material present in the peat.

### Chemical variables

Among chemical variables, soil water pH is one of the most frequently measured parameters in Member States (e.g., Denmark – Fredshavn 2022, Spain – Vegas et al., 2019, Silva-Sánchez et al., 2019a, Lithuania – Rašomavičius, 2015). These measurements can be carried out directly in the field using portable devices that are easy to operate and low in cost. The same applies to electrical conductivity, but this parameter is measured less frequently – for example, in Spain (Silva-Sánchez et al., 2019a and 2019b).

In Spanish mires (Silva-Sánchez et al., 2019a and 2019b), peat acidity is measured annually in the field using a pH-meter for solids. If no external impacts are observed, measurements are taken randomly from a representative number of peat samples. Where external impacts are visible, measurements are taken both in affected and unaffected areas. In Poland, pH is also used to assess the degree of habitat acidification, which may result from natural peat accumulation and reduced contact with groundwater, or from anthropogenic pressures such as artificially lowered groundwater levels due to partial draining (Mróz, 2013).

Soil nutrients are determined in laboratories in Spain, where total nitrogen, phosphorus, potassium and C/N ratio are analysed (e.g., Silva-Sánchez et al., 2019a). The C/N ratio is also measured in Danish mires (Fredshavn et al., 2022). However, these analyses are costly and therefore rarely used. Nitrogen deposition is measured only in the Netherlands (BIJ, 12).

Key chemical parameters analysed in Irish petrifying springs (habitat 7220*) include alkalinity, pH, nitrate, phosphate, chloride and calcium. In an Irish context, pH ranges from 7.0 to 8.47, with elevated alkalinity and high calcium concentrations commonly observed. The concentrations of nitrates and phosphorus were generally low. Any measurements falling outside of these ranges are likely to indicate springs under chemical pressure or stress (Denyer et al., 2023).

## Biotic characteristics: variables, metrics and measurement methods

### Compositional variables

**Plant species composition and the presence of typical species** are among the most frequently used variables across all Member States. For mires, both vascular plants and bryophytes are included, while for bogs, lichens are also considered. For habitat 7220* in Ireland, the presence of cyanobacteria, algae and diatoms is recorded (Denyer et al., 2023), and in Poland, bryophyte assessments include liverworts (Parusel, 2010).

In nearly all cases, assessments are based on lists of plant species that are characteristic, dominant, or typical of the particular habitat, focusing on the presence or abundance of such species. These species lists are generally similar across countries, but may vary in detail due to differences in species diversity across regions, regional land use history, or differing interpretations of the habitat type. Some methodologies record the full species composition at a given site, while others focus only on typical species.

In Belgium-Flanders (Oosterlynck et al., 2020) and the Czech Republic (Vydrová & Lustyk, 2014), species cover on permanent plots (25 $m^2$ each) is assessed using the phytocenological Braun-Blanquet scale. The method includes mandatory identification and recording of both species' composition and bryophyte cover. The assessment focuses on: a) changes in species composition (similarity indices); b) changes in dominant species; and c) changes in species number and species cover within the relevés. In Germany (BfN, 2017) and Poland, on site plant species inventories are conducted based on a reference list of typical plant species. In Slovakia (Šefferová et al., 2015), the sampling design involves an inventory of higher plant species and bryophytes at permanent monitoring sites.

**Plant indicators** are essential tools for assessing the ecological status of mires. As plants respond predictably to environmental conditions, they provide valuable insights into factors such as hydrology, nutrient availability, acidity, and human impact. In mire assessment, plant indicators are used to categorize species along a gradient from positive (indicating good condition and ecological integrity) to negative (indicating disturbance, degradation, or ecological imbalance).

Positive indicator species are evaluated based on their number or percentage within the site, using a reference list. For example, in Ireland, typical species of habitat 7220* (Petrifying springs with tufa formation) serve as positive indicators of good condition. A total of 26 high-quality indicator species is used, including 12 vascular plants, one algae, three liverworts, and ten moss species (Denyer et al., 2023).

Negative indicator species include nitrophilous species, whose presence and abundance signal eutrophication. This approach is used, for example, in France (Clément et al., 2022) and Belgium-Flanders (Oosterlynck et al., 2020). These species are recorded during phytosociological or floristic surveys at the plot level (Clément et al., 2022). In Germany, acidification is assessed by the increasing presence of acid-tolerant indicator species and the declining vitality of *Cladium* species in habitat 7210*(BfN, 2017).

**Animal indicators.** In France, faunal inventories of invertebrate groups such as arachnids, odonates, lepidopterans, dipterans, and orthopterans are recommended as wildlife indicators (Epicoco & Viry, 2015). For calcareous fens (habitat 7230), molluscs are recorded, considering both live individuals and empty shells, either at the scale of the habitat polygon or within a representative plot. For habitat 7220*, the target species include salamanders, odonates and crayfish (Clément et al., 2022). In Greece, the presence of bird and insect communities is recommended to be recorded (Dimopoulos, 2018). In Italy, any target species may be selected (Angelini et al., 2016). In Sweden, typical bird species are used as evidence of favourable conservation status in the habitat type (Götbrink & Haglund, 2010). A decline in the abundance of typical species may indicate different ecological changes, depending on species' specific requirements. Most typical bird species depend on large, open, treeless marshes and hydrologically intact conditions.

### Structural variables

**Plant functional types.** Among structural variables, vertical structure is commonly assessed and includes distinct layers such as mosses, grasses and herbs, dwarf shrubs, shrubs, and trees. These layers vary depending on mire type, hydrological conditions, nutrient availability, and other environmental factors. National methodologies include a range of variables to assess the functional structure of vegetation, typically expressed as cover, and such variables appear across all methodologies. These include:

- **Herb-layer cover.** For example, in Germany (BfN, 2017), for fen habitat 7140, the cover of typical transition mire vegetation with characteristic mosses is recorded.
- **Moss layer cover.** A high cover of peat-forming mosses (e.g., *Sphagnum* species) indicates adequate water saturation and active peat formation. In many countries, the cover of bryophytes is recorded as a percentage based on expert site assessment (e.g., Deak et al., 2014). In Poland, for bogs, both total moss cover and the proportion of hummock *Sphagnum* mosses within total moss cover are recorded (Koczur, 2015).
- **Cover of trees and shrubs.** The presence and extent of trees and shrubs on open mires are generally considered negative indicators. Typically, less than 10-20% cover is viewed as indicative of an undisturbed open mire, though this threshold varies between habitat types and Member States. High coverage of woody vegetation may suggest degradation, with impacts on hydrology, peat formation, and biodiversity. In Sweden (Götbrink & Haglund, 2010), remote sensing methods – such as infrared aerial photography – are used to monitor canopy cover, with field-based methods applied to smaller sites (less than 3 ha).
- **Cover of nitrogen indicators and invasive alien species.** An increase in the cover of such species is widely recognised as a sign of habitat degradation (e.g., Lithuania – Rašomavičius et al., 2015, Latvia – DAP, 2023, France – Clément et al., 2022, Germany – BfN 2017, Greece – Dimopoulos et al., 2018).

**Microrelief structure** is particularly important for bogs. It includes features such as hummocks, hollows, pools, and ridges, which play a critical role in water distribution within mires. This small-scale topography creates a diversity of microhabitats, each supporting different plant and animal species, and thus contributes significantly to overall biodiversity. However, the monitoring of these patterns is still rarely applied in most Member States.

For example, in Belgium-Flanders (Oosterlynck et al., 2020), the microrelief of habitat type 7110* is described using six structural elements: high humps, low humps, high flat areas, low flat areas, gullies and pools. Vaulted heights (humps) and lows (gullies and pools) form a distinct small-scale pattern. Humps are at least 10 cm high (occasionally exceeding 1m), oval to round in shape, and arrange in diameter from 0.5 m to 6 m. High humps are defined as those at least 25 cm high. Pools are deeper than gullies, with permanent inundation, while in gullies the water level may drop to ground level. The habitat is assessed as being in favourable status if high humps and pools are present but only in limited numbers.

In several countries, the area with bog hollow-hummock microtopography is recorded by expert judgement based on visual on-site assessment and orthophoto maps, typically expressed as a percentage (BfN, 2017; DAP, 2023; Stańko, 2010).

**Tufa formation** is a geological and ecological process that results in the development of unique and visually striking formations, which are significant both ecologically and hydrologically. In Belgium-Flanders (Oosterlynck et al., 2020), the cover of limestone tufa deposition is recorded for habitat 7220*. In Germany (BfN, 2017), both historical and recent tufa formation are assessed based on the presence of clearly recognisable, well-developed tufa structures (e.g., terraces, ridges or mounds) and visible tufa deposits (chalk ridges, encrusted moss), which are considered indicators of favourable habitat status. In Lithuania, the formation of calcareous deposits is evaluated as abundant, sparse, or present) (Rašomavičius et al., 2015). Ireland has developed a specific methodology for habitat 7220*, which includes variables such as the surface area of the active tufa-forming zone, as well as vegetation cover and morphological form (Denyer et al., 2023).

### Functional variables

Functional variables are assessed primarily in terms of anthropogenic influences on mires, including management and pressure factors. Most often, qualitative data collection methods are being used, with different evaluation procedures applied across Member States.

**Drainage structures** – such as ditches, canals, and drainage tiles – are among the most frequently recorded functional variables due to their significant, often detrimental impacts on mires.

Mapping of man-made drainage networks and erosion features is typically carried out through visual inspection. Drainage refers to the excavation of ditches of varying depths that lead to water loss from the peatland, causing a lowering of the water table and increased aeration. These ditches may cut across the peatland or be located at its edges (Silva-Sánchez et al., 2019). In Hungary, the depth and extent of drainage ditches are estimated as a percentage (Horváth et al., 2021). In Lithuania (Rašomavičius et al., 2015), the structure of visible drainage systems and their impact on the hydrological regime are evaluated using similar parameters. In Germany (BfN, 2017), favourable condition is assigned to habitat 7110* sites where drains are mostly overgrown, non-functional, or where peat has been rewetted over large areas. In contrast, the poorest status is attributed to with only slightly overgrown, still functional drains, and where bog-typical hydrology is only present at certain times or in small areas. In Poland, the extent of damage caused by drainage is determined based on the presence of ditches, their depth, water levels, and whether the water flows out or stagnates (Mroz, 2013).

In Denmark (Fredshavn et al., 2022), the following quantitative scale is used to assess drainage status: 1) No ditches, 2) All ditches non-functioning, 3) Old but functioning ditches (not maintained for approximately six years, 4) Ditches maintained within the last six years, 5) New ditches or ditches deepened within the past two years. A separate scale is used for the assessment of watercourses: 0) No natural watercourses; 1) Watercourses in a natural bed, with dead trunks and branches, and without regulation and purification; 2) Streams predominantly in natural bed, possibly with minimal purification; 3) Streams partially regulated, with occasional cleaning (not annual); 4) Watercourses regulated with frequent cleaning; 5) All watercourses piped.

**Management evidence**. In Denmark, evidence of grazing is recorded in the form of fencing, manure clumps, bitten herbaceous vegetation, and browsed bushes and trees. The presence of animals at the time of mapping is not required. Signs of hay cutting and bush clearing include uniform vegetation height without woody plant regrowth, as well as visible cutting tracks. The clearing of larger trees and bushes is considered a one-off intervention and is not registered separately, as it is reflected in changes in woody plant cover. The registration includes: the proportion of the area with grazing, the share with biomass removed (plains), the share with mowing where biomass is left behind, and the total extent of management activities (grazing, haying, and mowing combined). These elements are recorded using five categories covering the full range from 0 to 100 % (Fredshavn et al., 2016). In Spain, grazing impact is assessed annually through visual inspection and should be evaluated together with variables such as livestock density and nitrate concentration (Silva-Sánchez et al., 2019). In Lithuania, the intensity of restoration management measures - such as cutting of trees and bushes – is evaluated on a scale from 0 (no management) to 3 (intensive management) (Rašomavičius et al., 2015).

**Habitat degradation.** In Germany, on-site expert assessment is used to estimate degradation based on coverage and a description of the probable cause (e.g., military or recreational activities) (BfN, 2017). In the Czech Republic, an intensity scale is used in the field by mappers to assess habitat degradation: 0 – habitat without evident signs of degradation, or the degree of degradation is negligible; 1 – low degree of degradation; 2 – medium degree of degradation, or degradation is highly variable across the site; 3 – high and significant degradation; W – very high degradation and tendency towards unnatural habitat conditions (Lustyk, 2023).

The most frequently recorded impacts include:

- **Burnt area** is assessed annually by visual inspection and expressed as a percentage in Spain. Peat coring at depth using specific probes (e.g., Russian or Waardenar probe) is used to determine whether fire has affected deeper layers (Silva-Sánchez et al., 2019). In Ireland, expert judgement is based on visual on-site assessment, focusing on mosses and higher plants (Fernandez et al., 2014).
- **Peat cutting.** The presence of extractive activity is assessed annually by visual inspection in Spain (Silva-Sánchez et al., 2019). In Germany, on-site expert assessment covers the sampled area and an additional 500 m (BfN, 2017). In Poland, the extent of peat extraction damage and the potential for habitat regeneration should be evaluated. Relevant observations include the extraction method (manual, mechanical, or industrial), annual extraction volume ($m^3$), the percentage of mire

surface affected, and the time period during which peat extraction took place. This parameter helps determine the degree of habitat devastation (Mroz, 2013).

- **Fertilization** is assessed annually by visual inspection. Suspected fertilisation may be inferred from vegetation shifts towards grassland communities. Assessments should be complemented with measurements of soil pH and concentration of calcium, nitrogen, phosphorus and potassium (Silva-Sánchez et al., 2019).

### Landscape characteristics: variables, metrics and measurement methods

Landscape-related variables are not universally recognized in national methodologies and are rarely used. **Habitat area/extent** is assessed however in some national methodologies, typically as the size of each habitat patch.

In Italy, patch size and distance between mire patches are assessed using GIS (Angelini et al., 2016). In Spain, annual qualitative assessment of land use changes within the catchment is conducted (Silva Sánchez et al., 2019). Three categories are considered: Absence of significant change; Low deforestation (e.g., selective felling of some trees, shift to livestock, agricultural or moderate forestry use, or construction of minor infrastructure); and High deforestation (e.g., systematic felling of woodland on more than 20% of the catchment area, extensive land use change, or infrastructure development likely to affect the peatland's hydrological status). In Bulgaria, fragmentation of habitat polygons and the presence of anthropogenic structures (e.g.,buildings, roads) are recorded (MOEW, 2013). In Belgium-Flanders, connectivity and patch size are evaluated using GIS-based approach supported by threshold values and rules for determining habitat patch and cluster sizes (Oosterlynck et al., 2020).

Habitat 7230 Alkaline fens are species-rich wetlands fed by base-rich groundwater, characterized by stable water levels, low nutrient availability, and specialized plant communities including sedges, brown mosses, and often rare species. Protected area Brezinky, Slovak Republic.

## 2.2 Definition of ranges and thresholds to obtain condition indicators

Ranges and thresholds for mire habitats are defined in some national methodologies but absent in others. Some countries report insufficient information to establish thresholds, or note that threshold development is ongoing. In certain cases, ordinal scales are applied to selected variables, but these do not always correspond directly to categories such as “good” or “bad” condition. Other countries refer to broadly defined concepts – such as habitat degradation – rather than using clearly defined, objectively measurable variables.

Overall, documentation on the establishment of ranges and thresholds at the European level is insufficient. Expert judgement – rather than precise measurements – is used in most cases, even for variables that are inherently quantitative. Much of the available information is derived from vascular plant species composition, which also provides indirect insights into abiotic variables. Moreover, there are considerable differences among Member States regarding the ranges and thresholds applied, even for the same habitat type.

Some national methodologies that do include defined ranges and thresholds are those from Poland, Germany, Spain, Belgium-Flanders and Ireland. Others do not provide such definitions due to a lack of data to establish reference levels.

In Sweden, the effects of restoration measures are monitored using a dedicated approach known as action monitoring, which is based on permanent sample plots. Monitoring is carried out at regular intervals until the threshold values for the target indicators – specific to the habitat type – are met (Götbrink & Haglund, 2010).

Most EU Member States use a standardized three-category system to assess reference levels: FV (favourable), U1 (unfavourable – inadequate), and U2 (unfavourable – bad).

In Germany (BfN, 2017), thresholds are assigned to each variable to classify habitat condition into three categories: A = excellent conservation status, B = good conservation status, C = medium to poor conservation status. In Netherlands, a similar three-tier system is used, with categories defined as: High = excellent conservation status, Middle = good conservation status, Low = medium to poor conservation status.

### Abiotic characteristics

**Physical state variables.** Among physical variables, only a few Member States have set thresholds for water level fluctuation. These are recorded methodologies from Poland (Koczur, 2012; Stańko, 2010; Buczek, 2010; Parusel, 2010), Germany (BfN, 2017) and Bulgaria (MOEW, 2013).

Thresholds are most often expressed quantitatively as the maximum depth of the water column bellow the ground surface, either for individual habitat types or for groups of habitats. Large fluctuations usually indicate drainage impact. If the water level drops 20 to 30 cm below the surface, such sites are typically assessed as having an unfavourable–declining status (Table 7).

Threshold values for peat bulk density and ash content have also been established through biogeochemical investigations in the Atlantic region of Spain (Silva Sánchez et al., 2019a).

### Table 7. Examples of reference levels for habitat 7140

| Variable | Reference level / Threshold / Condition indicator | Habitats | Reference |
|---|---|---|---|
| **Water level** | **FV** – water level less than 10 cm below the ground<br>**U1** – water level 10-20 cm below the ground<br>**U2** - water level 20 cm below the ground | 7140 | Koczur, 2012 |
| | **FV** – high water saturation, hydrological regime typical of transitional mire, and/or wet pools present all year round<br>**U1** – temporary drying out, hydrological regime typical of transitional mire, and/or wet pools present part of the year<br>**U2** - longer dry periods, no transitional mire hydrological regime, only ephemeral pools | 7140 | BfN, 2017 |

**Chemical state variables.** When applied, thresholds for several chemical parameters are typically expressed quantitatively, based on measurement results. However, this approach is used in only two Member States.

In Spain, thresholds are defined for individual mire habitat types and include water and peat pH, electrical conductivity, C/N ratio, and the content of nitrogen (N), phosphorus (P), and calcium (Ca) (Silva-Sánchez et al., 2019). In the Netherlands, reference levels have been established for external nitrogen deposition affecting mire habitats (Table 8).

### Table 8. Examples of reference levels for nitrogen deposition across all mire types in Netherlands

**High indicates low nitrogen deposition and is considered FV; middle indicates an intermediate nitrogen deposition level and is considered U1; low indicates high nitrogen deposition and is considered U2**

| Variable | Reference level / Threshold / Condition indicator | Habitats | Reference |
|---|---|---|---|
| **Nitrogen deposition** | **High** – if < 10 kg or < 710 mol<br>**Middle** – if 10-18 kg or 710-1280 mol<br>**Low** – if > 18 kg or > 1280 mol | 7140 | BIJ12 |
| | **High** – if < 5kg or < 360 mol<br>**Middle** – if 5-10 kg or 360-710 mol<br>**Low** – if > 10 kg or > 710 mol | 7110*, 7120 | BIJ12 |
| | **High** – if < 11 kg or < 830 mol<br>**Middle** – if 11-18 kg or 830-1280 mol<br>**Low** – if > 18 kg or > 1280 mol | 7150, 7210*, 7220*, 7230 | BIJ12 |

## Biotic characteristics

### Compositional variables

**Species composition and typical species.** Several national methodologies apply a three-level system based on the number of typical mire species – high, medium and low. Both vascular plants and mosses are used for this purpose. The assessment of typical species representation is based on species count, with lists of typical species selected for each habitat type separately by expert judgement. These lists may differ between countries due to expert bias and biogeographical variation in species composition. In Ireland, the number of positive indicator species is used as a basis for assessment (Perrin et al., 2014; Denyer et al., 2023).

Threshold values for categorising into the three levels are, in most cases, also determined through expert judgement (Table 9).

### Table 9. Examples of reference levels for species composition in habitat 7110*

| Variable | Reference level / Threshold / Condition indicator | Habitats | Reference |
|---|---|---|---|
| **Species composition** | **FV** – at least 3 *Sphagnum* species and 2 vascular plant species from the list of characteristic species<br>**U1** – at least 2 *Sphagnum* species and 2 vascular plant species from the list of characteristic species<br>**U2** – at least 1 *Sphagnum* species and 1 vascular plant species from the list of characteristic species | 7110* | Stańko, 2010 |
| | **Quality A** – typical plant composition present<br>**Quality B** – typical plant composition mostly present<br>**Quality C** – typical plant composition only partly present | 7110* | BfN, 2017 |
| | **High** – at least 6 qualifying mire species are present, with at least 4 covering more than 15% of the surface area within their respective species groups<br>**Middle** – 3-5 qualifying mire species are present, or more species are present but the criteria for "High" status are not fully met<br>**Low** – the above criteria are not met | 7110* | BIJ12 |

## Structural variables

Structural variables are mostly assessed by evaluating the cover of the targeted habitat and the vertical (moss and scrub layer) and horizontal structures (microrelief features such as hummock-hollow formations, and cover of tufa deposits) of mire habitats. Cover is typically measured as a percentage or ratio. These quantitative values are often simplified into three condition categories (e.g., FV > 70%, U1 > 40%, U2), or in some cases one threshold category (e.g., good conservation: ≤ 30% cover), using various reference levels set by experts for individual habitat types (e.g., Buczek, 2010; BfN, 2017; Silva-Sánchez et al., 2019; Deak et al., 2014; Oosterlynck et al., 2020). In France, thresholds are often derived through statistical analysis (Clément et al., 2022).

Within the vertical structure, moss cover plays a critical role. Although total moss cover is often recorded in Member states, reference levels are rarely defined. For example, the bryophyte layer cover for habitat 7210* is classified as FV if 80-100%, U1 if 40-79%, and U2 if <40% (Deak et al., 2014). The proportion of total moss cover that is composed of brown mosses is important for calcareous fens: for habitat 7230, FV is defined as total moss cover > 50% with brown mosses > 70% of total moss cover (Koczur, 2012). For bogs and poor fens, the proportion of *Sphagnum* mosses is a key metric: for habitat 7110*, FV is defined as total moss cover > 50% and hummock-forming *Sphagnum* species cover > 25% of the total moss cover (Stańko, 2010).

The cover of negative indicator species – indicating nutrient enrichment or acidification – is assessed in several countries, including Germany (BfN, 2017), the Netherlands (BIJ 12), Belgium-Flanders (Oosterlynck et al., 2020) and Poland (Koczur, 2012; 2015; Buczek, 2010; Parusel, 2010).

**Table 10. Examples of reference levels for the hummock-hollow structure in bogs (habitat 7110*) and tufa deposit structures in habitat 7220***

| Variable | Reference level / Threshold / Condition indicator | Habitats | Reference |
|---|---|---|---|
| **Hummock-hollow structure** | **Quality A** – Hummock-hollow structure present.<br>**Quality B** – Structure absent, but more than 50% of the area is covered with regeneration zones featuring typical raised bog hollow species, or drained areas with typical raised bog hummock species present.<br>**Quality C** – Structure absent, and less than 50% of the area is covered as described in B. | 7110* | BfN, 2017 |
| | **FV** – Typical hummock-hollow structure with characteristic vegetation; hummocks dominated by *Sphagnum* species.<br>**U1** – *Sphagnum* carpet with scattered *Sphagnum* hummocks.<br>**U2** – Absence of hummock-hollows structure or hummocks formed only by *Eriophorum vaginatum*. | 7110* | Stańko, 2010 |
| **Tufa deposit structures** | **Quality A** – Clearly recognisable, well developed tufa structures (e.g., terraces, ridges or mounds).<br>**Quality B** – Clearly recognisable tufa deposition (e.g., chalk ridges, encrusted moss), but only weak development of larger tufa structures.<br>**Quality C** – Few but recognisable tufa formations, with no larger structures. | 7220* | BfN, 2017 |
| | Tufa deposits (cover): FV > 5%; U1 > 0 up to 5%; U2 – 0% | 7220* | Parusel, 2010 |

## Functional variables

Thresholds for functional characteristics of mires are rarely defined in national methodologies and are typically based on the presence of negative processes at the site level. These include, for example, the extent of drained peat (BfN, 2017), evidence of burnt areas (Silva-Sánchez et al., 2019) and the result in impact on vegetation (Fernandez et al., 2014), evidence of peat cutting (BfN, 2017), and the cover of alien plant species and neophytes (Koczur, 2012; Stańko, 2010; Buczek, 2010; BfN, 2017). These characteristics are generally documented through expert-based qualitative assessments, such as estimating the percentage of peatland damage or coverage. For instance, in habitat 7120* (BfN, 2017), the extent of drained peat is assessed based on the presence and condition of drainage indicators: Quality A = drains mostly overgrown, no longer functional, or peat rewetted over large areas; Quality B = drains partly overgrown, with decreasing drainage influence due to natural processes or localised rewetting (rewetting may be limited in extent); Quality C = drains only slightly overgrown, still functional, with typical bog hydrology present only at certain times or in small areas.

## Landscape characteristics

Thresholds for landscape-level variables are rarely developed by Member States for mire habitats. In Belgium Flanders (see section 2.4 in Oosterlynck et al., 2020), two separate variables are used: the area of a specific habitat type and the area of a functionally related cluster of habitat types. Whether the condition of a habitat type is assessed as favourable (FV), moderately unfavourable (U1) or very unfavourable (U2) depends on both the percentage deviation from the reference area and the trend over the last 12 years. For favourable status (FV), the area must be equal to or greater than the reference area and be stable or increasing. A significant decrease (> 12% over 12 years) or a deviation from the reference area greater than 10%, leads to a very unfavourable regional situation (Paelinckx et al., 2019).

## 2.3 Aggregation methods at the local scale

Ecological assessment requires the integration of multiple physical, chemical, and biological aspects. The method chosen to aggregate such partial assessments into an overall evaluation can significantly influence the outcome. Two aggregation methods are commonly used in current practice: the weighted arithmetic mean (additive aggregation) and the one-out, all-out method (minimum aggregation) (Langhans et al., 2014).

Variations of the one-out, all-out principle include approaches where a majority of variables must achieve good status. This principle follows the general concept that the ecological status assigned to a habitat is determined by variable with the lowest status. As such, the one-out, all-out method results in a “worst case” outcome (see Borja et al., 2014).

More refined assessments involve weighting the importance of individual indicators, acknowledging that not all variables are equally significant. This results in a more nuanced final evaluation (Oosterlynck et al., 2020).

This section summarises the aggregation methods used by Member States to assess the structure and functions of mires at the local scale (typically at the level of the monitoring plot). These assessments integrate abiotic and biotic variables measured in the field. Once each variable is evaluated – either quantitatively or categorically (e.g., good/favourable, medium/unfavourable, low/bad condition), – aggregation is carried out either via arithmetic operations (for quantitative values) or aggregation rules. In some cases, weighting is applied to individual variables according to their relevance for habitat condition, allowing for a more differentiated final assessment.

Although all Member States have detailed methodologies to define and measure variables for the structure and functions criterion, not all have established a clear aggregation methodology for assessment at the local scale. In some countries, algorithms for aggregating habitat condition at Natura 2000 sites are under development (e.g., Czech Republic, Latvia). Some Member States (e.g., Spain, Poland, Ireland) report using distinct aggregation procedures for different mire types, while in most Member States the procedure is common across all habitats or groups of habitats.

In Ireland (Fernandez et al., 2014), assessment is based on evaluating the condition of habitat quality. For Active raised bogs (habitat 7110*), the conservation status is determined by the percentage of the most intact ecotope types within the habitat. The target is that at least 50% of the area should consist of the most natural and well-functioning ecotope types.

For habitat 7220*, conservation scores were calculated for each spring location (Lyons & Kelly, 2016), ranging from 1 (low habitat quality) to 10 (high habitat quality). The conservation score was based on the total of individual scores for: species diversity (score 1 – 4), the number of high-quality indicator species, the extent of tufa formation (score 1 – 4), and the presence of other positive characteristics such as extensive tufa formation (score 1 for each characteristic).

In the methodology used for assessing acid bogs in Spain (Silva-Sánchez et al., 2019a), two groups of variables are considered: extrinsic factors, which have a direct effect on the peatland and can be assessed through visual inspection (e.g., artificial drainage, percentage of typical and transformed vegetation cover, fertilization, fires, commercial peat extraction, infrastructure, livestock); and intrinsic factors, which correspond to peat and water properties that can be measured and quantified.

The intrinsic group includes six mandatory variables: peat pH, peat density, ash content, C/N ratio, water pH and electrical conductivity (see Table 11). The sum of the values obtained from these measurements is used to calculate the Intrinsic Factors Index (IFI), which ranges from 0 to 18. As a guide, IFI values below 8 indicate an unfavourable-poor status; values between 8 and 13 indicate an unfavourable-inadequate status; and values above 13 correspond to a favourable status.

**Table 11. Threshold values for variables assessed for Atlantic bogs in Spain** (adapted from Silva-Sánchez et al., 2019a)

| **Intrinsic factors (variables)** | **71310* and 7130*** | | |
|---|---|---|---|
| **Threshold values** | **Optimal** | **Suboptimal** | **Poor** |
| **Peat** | | | |
| **pH of peat** | 3.0 – 4.5 | 4.5 – 5.0 | > 5 |
| **Peat density** | < 0.25 | 0.25 – 0.75 | > 0.75 |
| **Ash content (%)** | < 10% | 10 – 50 | > 50 |
| **C/N ratio** | 24 - 30 | 24 – 18 | < 18 |
| **Water** | | | |
| **pH of water** | 3.0 – 5.0 | 5.0 – 5.5 | >5.5 |
| **Electrical conductivity (µS/cm)** | < 50 | 50 – 200 | > 200 |
| **IFI value for each threshold** | **3** | **1** | **0** |
| **Artificial drainage** | Without drainage | | With drainage |
| **Typical vegetation cover and transformation** | >90% vegetation cover; 0% transformed veg. | 70-90% vegetation cover; 20% transformed | 70% vegetation cover, >20% transformed |
| **Peat extraction** | Absent | | Present |
| **Fires** | Absent | Present, but only superficial or affecting <10% of the area | Present, affecting both surface and depth, >10% area |
| **Infrastructure occupation** | Without infrastructure | Infrastructure with damage mitigation | Infrastructure without damage mitigation |
| **Livestock load** | None or moderate | Medium | High |
| **Fertilization** | Without fertilization signs | | With fertilization signs |

The assessment begins with an analysis of the direct extrinsic factors. The absence of significant effects indicates a favourable condition. The presence of either a binary extrinsic factor (absence/presence), a ternary factor (high/medium/low) at its maximum degree or three, or three of more ternary factors at an intermediate degree implies an unfavourable-bad. Any other combination indicates unfavourable-inadequate condition (Figure 3).

The intrinsic factors are assessed by calculating the Intrinsic Factors Index (IFI), which represents the sum of the values assigned to six measured variables:

IFI= pH of peat + peat density + ash content + C/N ratio + water pH + electrical conductivity

The resulting index ranges from 0 to 18. According to the methodology, IFI values below 8 indicate an unfavourable-poor condition, values between 8 and 13 indicate an unfavourable-inadequate condition, and values from 14 to 18 indicate a favourable condition (Figure 4).

**Figure 3. Visual scale for assessing extrinsic factors, from unfavourable-bad to favourable condition**

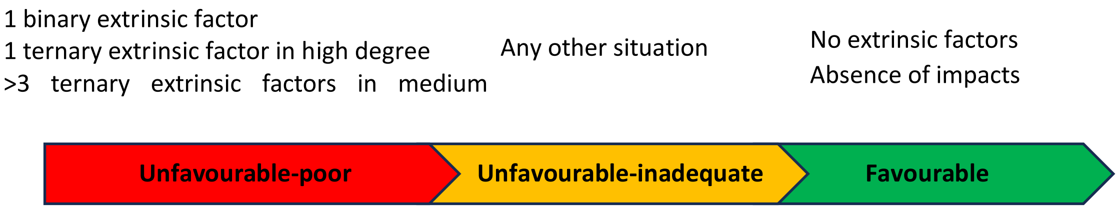



**Figure 4. Ranges of Intrinsic Factors Index (IFI) indicating favourable and unfavourable condition categories**


The numerical value of the Intrinsic Factors Index (IFI) will determine the habitat condition according to the ranges shown above. However, this value should be considered together with the assessment of extrinsic factors in order to understand the degree of transformation of peat properties. If the habitat is classified as having an unfavourable status based on extrinsic factors, but the IFI value is 14 or higher, more detailed monitoring should be carried out to explore the reason for the discrepancy. Possible explanations may include resilience of the peatland to impacts, lack of sample representativeness, or sampling carried out at an inappropriate time of year.

For example, drainage impacts may be present, but not yet severe enough to significantly alter the properties of peat or water, meaning that ecosystem functions are not yet compromised. In such cases, installing water table monitoring systems may be advisable to detect potential short-term changes in hydrology. It should be noted that this is a novel methodology currently under testing, and adjustments to the monitoring approach may be introduced. Conversely, if no damage is observed but the IFI value is below 14, the condition will be determined based on the IFI, which takes priority.

In the Spanish methodology for assessing the conservation status of calcareous mires (Silva-Sánchez et al., 2019b), the evaluation is based on the following criteria:

- **Favourable**: The habitat is considered to be in good condition when at least 90% of its surface area contains characteristic, non-transformed vegetation, shows no signs of artificial drainage or extractive activities, and has a peat pH of ≥ 5.5, and no other signs of alteration are identified in more than the 10% of the habitat surface.
- **Unfavourable-inadequate:** The habitat falls into this category when between 10% and 30% of its surface area is affected by vegetation alteration, artificial drainage, fertilisation, or other disturbances.
- As with acid bogs, intrinsic (informative) variables are determined in order to provide early warning signs of degradation before changes become evident through visual inspection of extrinsic factors.

In Poland, the assessment of the 'specific structure and functions' of a habitat is composed of several to more than ten indices. The method of deriving the overall assessment from these indices is described in detail in the methodology for each habitat type and is based on expert judgement (see example for habitat 7230).

**Example of local-scale aggregation for Calcareous fen habitat 7230 based on expert assessment (Wołejko et al., 2019)**

The assessment of conservation is based on the description and evaluation of selected aspects of ecosystem structure and functions – referred to as structure and functions indices – using a three-point scale: favourable (FV), unfavourable-inadequate (U1) and unfavourable-bad (U2). The following indices are evaluated in the entire monitoring transect:

1. Percentage of area occupied by the habitat within the transect (if the habitat is preserved only as a mosaic of patches with other ecosystems): 80 – 100% is assessed as FV, 50 – 80% as U1, and < 50% as U2.
2. Number of characteristic species. If 9 or more characteristic species are present or the total cover by characteristic species exceeds 50%, the conservation status is rated as FV; 4 – 8 characteristic species and total cover of 20 – 50% is assessed as U1; lower values are rated as U2.
3. Dominance structure. Dominance by characteristic species of the habitat is rated as FV; dominance by species not included among characteristic species is rated as U2.
4. Cover and structure of the moss layer. Total moss cover exceeding 50%, with more than 70% of brown mosses, is rated as FV; total cover of 20 – 50%, with 20 – 70% of brown mosses, as U1; lower values, including absence of brown mosses or dominance by *Sphagnum* mosses, as U2.
5. Presence of alien invasive species. Absence of these species is evaluated as FV, 5% of invasive species as U1, and greater percentage as U2.
6. Presence of expansive herbaceous plant species. Their lack is evaluated as FV; up to 5% cover as U1; greater percentage as U2.
7. pH value of the surface peat layer, measured at five points along the transect using a field pH-meter or estimated colorimetrically using Hellige's method.
8. Overgrowth by trees and shrubs. Absence or presence of only single trees is rated as FV; up to 15% cover by trees and shrubs as U1; greater percentage as U2.
9. Water conditions on the day of observation, assessed at five points on the transect: water table between 10 cm below and 2 cm above fen surface level is judged as FV; between 20 cm below and 10 cm above ground level as U1; values more distant from the peat surface as U2. A practical criterion for FV status is that water should always be visible while walking on the fen, at least up to the height of the sole.
10. Historical and current peat extraction. Traces of historical extraction affecting up to 5% of the area, without current activity, can be rated as FV; contemporary sporadic small-scale extraction or historical larger-scale extraction reduces the rating to U1; ongoing larger-scale extraction results in U2;
11. Presence of artificial drainage system. No ditches or fully neutralized impact is evaluated as FV; ditches filled with vegetation or blocked enough to have only slight impact are rated as U1; ditches visibly worsening water conditions are rated as U2.

Based on the above-listed indices, an expert evaluates the overall status of the parameter "structure and functions" on the three-point scale (FV-U1-U2). The following indices are considered cardinal – meaning they are the key indicators of the structure of functions of the natural habitat: characteristic species, cover and species composition of mosses, pH range, expansive herbaceous plant species, encroachment of shrubs and samplings, and water conditions. The overall rating for “structure and functions” cannot be higher than the lowest rating among these cardinal indices. The interpretation of the remaining indices is left to expert judgement.

In the Belgium-Flanders methodology (Oosterlynck et al., 2020), a common approach is used across all habitats, involving weighted aggregation and a majority rule for integration on the local scale. Each individual indicator is evaluated using only two categories: favourable or unfavourable status. This approach differs significantly from that of most other Member States, which typically use three conservation status categories – FV, U1, and U2. In contrast, Flanders applies these three categories only at the biogeographical level, not for individual habitat assessments. Weighting is applied based on a set of general rules, guided by the following considerations:

- Indicators that significantly hinder the long-term favourable condition of the habitat, and which would require more than standard nature management efforts to restore, are considered highly important.
- Indicators that are almost entirely controlled through management are also considered important.

The overall conservation status of a habitat at a specific location (favourable or unfavourable) is determined by assessing the relevant indicators at the local level. To reach a final judgment, the indicators are integrated to provide a comprehensive evaluation of the habitat’s condition. This local conservation status assessment is applied to entire habitat patches, particularly in contexts such as appropriate assessments for specific projects.

In Germany (BfN, 2017), several criteria (variables) are assessed for each habitat type, grouped into the following categories: 1) completeness of typical habitat structures, 2) completeness of the habitat’s typical species inventory, and 3) impairments. Each variable is evaluated using three categories: A = excellent conservation status, B = good conservation status, and C = medium to poor conservation status. These individual evaluations are subsequently summarised using an accounting matrix to produce an overall assessment of the parameter “specific structures and functions” for each sample plot. As a result, the proportions of sample areas falling into the three value levels (A, B and C) are determined, serving as a basis for further aggregation at higher levels.

In Slovakia (Šeffer & Lasák 2022, ined.), the aggregation of variables for non-forest habitats, including peatlands, at the local scale is performed using ordination in a multidimensional space, where each axis represents a different assessed variable, such as typical or indicator species, vertical structure, area change, influences or management, and future prospects.

Since these variables exhibit different levels of variability, they are normalized using min-max scaling (0–1) to ensure comparability. This approach allows the position of a monitoring record in the multidimensional space to be interpreted based on changes in the individual variable scores along each axis.

The local conservation status is then evaluated by measuring the Euclidean distance of a monitoring record from the best possible reference record, representing the highest habitat quality. A suitability coefficient is derived to express the quality of the monitoring record.

Thresholds are defined for four conservation status categories, based on distances from the best monitoring records, which are divided into equal intervals: A = excellent conservation status, B = good conservation status, C = poor, and D = bad conservation status.

In France (Epicoco & Viry, 2015; Clément et al., 2022), the methodology for assessing conservation status at the local scale is based on three key parameters:

1. Habitat composition, structure, and functions.
2. Deteriorations affecting the habitat.
3. Changes in its area within the site.

Each parameter comprises specific criteria, which are linked to one or more indicators (variables). The observed value of each indicator is compared against a threshold value, and a score is assigned based on the deviation.

- If an indicator is unfavourable, it receives a negative score.
- A final score is then calculated by summing all individual scores and adding a base value of 100.

The conservation status is determined by mapping the final score into a scale representing the conservation status gradient, which may be further divided into distinct status levels.

Once the condition is assessed at the local level using the procedures described above, the results can be aggregated at broader scales, such as the biogeographical region, as outlined in the next section.

## 2.4 Aggregation at biogeographical scale

Monitoring of habitat types for conservation status assessment focuses on large-scale spatial levels, namely the biogeographical regions of Europe or their respective proportions of EU Member States. Aggregation at the biogeographical scale involves combining data from multiple sites within a given region to provide a comprehensive overview of the habitat's condition and trends.

Most Member States use the three-grade EU assessment system for evaluating the degree of conservation: A – excellent; B – good; C – average or bad.

Additionally, most Member States follow the recommendations of the Article 17 reporting guidelines when aggregating local condition assessments to derive an overall assessment at the biogeographical scale. These guidelines state: "If 90% of the habitat area is considered to be 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'".

Some Member States use the "one-out, all-out" approach (minimum aggregation, sensu Langhans et al., 2014) for weighting the indicators at both the local and the biogeographical scales. Under this approach, a favourable conservation status requires that all conditions important for the specific mire habitat type are met at all the assessed locations.

Other Member States use different indices and descriptive statistical methods for aggregation at larger spatial scale. For example, in Lithuania (Rašomavičius et al., 2014), the national-level assessment of habitat condition is based on a multivariate approach, involving statistical evaluation of all parameter values using non-hierarchical cluster analysis methods such as K means. This common data matrix procedure groups surveyed sites based on their indicator values and assigns them to conservation condition classes. Ordinal analysis techniques such as Principal Component Analysis (PCA) are then used to visualise and assess the relationships between these groups.

In Belgium-Flanders (Paelinckx et al., 2019), an alternative aggregation approach is used at this level. A statistically robust sample is taken for each habitat type, measuring a set of habitat-specific indicators.

1. Integration across sample sites: For each indicator, data from multiple sites are combined to assess whether the indicator is favourable or unfavourable at the Member State or biogeographical level.
2. Additional Member State-level indicators: Two broader indicators - spatial configuration/fragmentation and Red List status of typical species - are included, as they can influence the final assessment.

Finally, other Member States either do not provide information regarding aggregation methods or state that such methods are still under development and not yet ready for use.

## 2.5 Selection of localities

The number of sample plots per habitat type and the methods used to select them differ considerably between Member States. Overall, most Member States apply at least a partly systematic selection based on the distribution, size and characteristics of habitat types and/or other factors (Ellwanger et al., 2018).

One of the challenges of monitoring schemes is that sample plots may be selected according to the number and distribution of habitat occurrences, but without accounting for the widely varying area sizes of those occurrences. This results in a lack of representativeness in terms of the total distribution area of a habitat type.

Furthermore, in most Member States, no information is available on the statistical robustness of the sample design with respect to the detectability of changes in habitat status (across two or more reporting periods) based on the analysed samples (Ellwanger et al., 2018).

Based on our analysis, the number of sample plots in most Member States primarily depends on the frequency of occurrence of a given habitat type. The main approaches to selecting localities for monitoring are:

(1) Preferential selection using expert knowledge; (2) Random or regular stratified selection, conducted using GIS tools, based on habitat or land-cover maps and geographic grids.

If sample plots are primarily selected based on expert opinion, criteria such as geographical distribution, size of habitat occurrences, and variation within individual habitat types are typically considered. Monitoring sites are also chosen to reflect a range of conservation statuses, from undisturbed mires to sites significantly affected by various pressures. However, this approach poses challenges for statistical representativeness, as such sampling does not allow for the calculation of confidence intervals in the final results.

Most Member States use permanent plots, apply standard assessment schemes, and include areas both within and outside the Natura 2000 network. For example, in Poland, preferential selection based on expert knowledge was applied to ensure appropriate representation of natural habitat occurrences in terms of number, distribution, and degree of threat. All rare and endangered habitats found in only a few locations are subject to monitoring. To capture habitat variability, monitoring sites were selected both in the core and at the periphery of the habitat's range, as well as in protected and non-protected areas (Mróz, 2017).

In Slovakia, permanent monitoring localities (PMLs) for habitats were selected using a stratified selection process in GIS, based on the following criteria (Šefferová Stanová et al., 2015):

- **Area size**: Ranging from 0.5 to 70 ha.
- **Target habitat dominance:** Ensuring that the target habitat is dominant within the PML, particularly in habitat complexes.
- **Biogeographical representation:** PMLs were proposed and assessed independently within each biogeographical region (Alpine and Pannonian).
- **Geographical coverage:** Ensuring a well-distributed network across the entire range of the habitat, avoiding large gaps or excessive concentration in a single area.
- **Habitat quality representation:** Including a wide range of habitat conditions, from high-quality sites to degraded areas, to enhance overall representativeness.
- **Rare habitats:** All known occurrences of rare habitats were included in the monitoring network.

For the Spanish mires (Silva-Sánchez et al., 2019a, b), the selection of monitoring localities is based on three types of criteria, assessed using a dichotomous decision system (Yes=1, No=0):

- **Environmental criteria:** Water quality; location in catchment areas or headwaters of rivers and streams; functions such as landslide prevention and sediment retention; presence of protected or endemic species; biodiversity supplementation index of the area; inclusion in a peatland complex.
- **Cultural criteria:** Heritage and ethnographic values.
- **Scientific criteria:** Function as natural paleoenvironmental archives (resolution, integrity, chronology); relevance for climate evolution studies; and evolutionary association with geomorphological elements of interest.
- **Conservation criteria:** In situ conservation status of the functional unit and the type of impacts it is subjected to.

For calcareous mires (Vegas et al., 2019), priority was given to sites representative of the different types of tufa formations generated by bryophytic communities in carbonate-rich waters. Selected sites meet the following criteria:

- Currently active formations exhibiting both compositional and structural quality.
- Significant geographical range and distribution, with priority given to sites of high conservation value.
- Location in areas of conservation interest, due to rich flora, rarity, or advanced ecological maturity.
- Clearly distinguishable active and inactive zones, allowing for long-term monitoring of habitat development.
- Representation of different basin types, including:
    - Sites with reduced water supply, enabling controlled monitoring of system variables and processes.
    - Sites with complex water supply, offering insights into diverse hydrological conditions.
- Inclusion of areas with varying degrees of human impact, enabling comparisons across different levels of anthropogenic alteration.

A detailed list of the proposed monitoring sites and their characteristics is provided.

## 2.6 General monitoring and sampling methods

Peatland monitoring at the field scale collects information on the condition, functioning, and changes of peatlands over time. These methodologies can be broadly categorized into field-based assessments, remote sensing techniques, and integrated approaches combining multiple data sources.

Most Member States apply sample-based monitoring schemes which rely on field mapping of individual occurrences of target habitats. These schemes vary considerably in the number and size of monitoring plots, as well as in sampling design and layout. Approaches to recording plant species composition and abundance also differ, using various methods such as phytosociological relevés following the Braun-Blanquet scale, percentage estimates, Tansley scale, Londo-scale, or a three-grade abundance assessment (e.g., low / medium / high). The recording of abundance is a core component of the procedure. In several countries, the documentation of monitoring sites includes requirement to photograph the habitat.

This section summarizes the monitoring and sampling methods used by Member States, focusing on the design of monitoring plots, their size, the types of variables recorded, monitoring frequency, and timing of sampling. The use of remote-sensing as the primary data collection method remains limited among Member States. However, Sweden and Finland are testing the application of remote sensing techniques for the monitoring of aapa and palsa mires, which cover extensive areas.

In Poland, the monitoring methodology for most natural habitats involves marking a 200 m long and 10 m wide transect at each monitoring site, covering a total area of 2000 $m^2$. Phytosociological relevé samples are taken at the beginning, middle, and end of the transect. These relevés – standard vegetation descriptions used in phytosociology – allow for detailed analysis of species composition and enable floristic comparisons between locations across the country. In addition, the conservation status of the habitat is assessed across the entire transect area (also including areas between the relevé points), using a system of parameters and indices and a detailed research methodology (Mróz, 2017).

In the Czech Republic, the conservation status is assessed at permanent monitoring plots (PMPs), each covering 25 $m^2$ every six years. A PMP is a pre-defined polygon where a specific habitat occurs, typically representing a homogeneous area with consistent management. The assessment may include: (a) changes in species composition (similarity indices); (b) changes in dominant species; (c) changes in species richness and species cover in relevés; (d) presence of rare species; (e) rate of change in relation to polygon size; (f) distance to the nearest segment of the same habitat (metapopulation context); (g) influence of surrounding land use and the management practices (Vydrová & Lustyk, 2014).

In Lithuania, the monitoring of habitat structure and functions is carried out within habitat polygons, which are selected from habitat monitoring squares to proportionally include both protected areas (including Natura 2000) and unprotected areas within the square. Monitoring is conducted along a transect 200 m long and 10 m wide (approximately 2000 $m^2$ area), selected within the polygon. If the polygon is smaller than the required transect, observations are carried out as far as possible within a reduced-size transect. Normally, the transect follows a straight axis; however, if this is not feasible due to the polygon's irregular shape, a broken-line transect is used. In specific cases, the transect may coincide with the entire polygon area. In such cases, the habitat must be specified in the monitoring description (Rašomavičius, 2015).

Observational data are collected during fieldwork. At each monitoring location, the field researcher completes four questionnaires:

**1) General questionnaire** – Records general information about the monitoring site, with some data possibly obtained from auxiliary sources and databases.

**2) Impact and threat assessment questionnaire** – Documents current pressures and potential threats affecting the habitat.

**3) Floristic-phytosociological description** – Includes three phytosociological relevés conducted at the beginning, middle and end of the polygon.

4**) Habitat structure and functions questionnaire** – Assesses the physical and biological characteristics relevant to the habitat's structure and function.

During each monitoring period, at least three observations are conducted within each monitoring square and its designated monitoring locations.

- Observations are distributed across 16 monitoring squares over a 12-year cycle.
- Each monitoring year includes:
    - Field surveys covering the entire monitoring square, assessing habitat area and overall condition.
    - Detailed monitoring at all designated locations within the square, focusing on habitat structure and functions.

The collected data are then used to assess conservation prospects and support management planning.

In Latvia (DAP, 2023), monitoring is conducted using two field forms per polygon: one for the vegetation plot and one for habitat structures and impacts. To identify typical species within the monitoring area, a 10 x 10 m vegetation plot is established at the most representative location within each transect. A vegetation description is prepared using the Braun-Blanquet approach, with species cover recorded as percentages. The coordinates of the southwest corner of the vegetation plot are documented.

In Denmark, each locality includes 8–12 small plots (0.5 m x 0.5 m) randomly placed, each with an associated 5 m radius circle centered on the sample plot. Each circle may only be assigned to one habitat type per monitoring year. Monitoring is conducted from May through October, with specific time windows designated for different habitat types (Fredshavn, 2022). Habitat types may occur in a mosaic within the area, meaning that multiple habitat types can be present at a single locality, following the habitat grouping described in (Fredshavn et al., 2016).

In France, different sampling strategies are used to assess the conservation status of habitats at the scale of a Natura 2000 site. Since sampling cannot always be conducted across the entire habitat area, a balance must be struck between the resources available for evaluation (human and material) and the desired level of accuracy. When the number of habitat polygons is limited, the method can be applied to each polygon by selecting one plot per polygon (full sampling). Fragmented surveys (equivalent to one plot) are also possible if two habitat patches can be considered part of the same polygon (i.e., they share the same physiognomy, floristic composition, and management). When the number of polygons is large, random sampling of polygons may be applied. However, it is essential to ensure that the sample accurately represents the entire site (Clément et al., 2022). In France, a sampling strategy and monitoring scheme for mire habitats at the biogeographical scale has not yet been established but is currently under development.

In Spain, most bogs are small enough to allow visual inspection by walking around the perimeter and making transects along it. For habitat 7130*, inspection from elevated ground or the use of drones is recommended. Samples should always be taken at the mesotope scale; in the case of blanket bogs and bog complexes, a representative number of the different mesotopes forming the macrotope should be selected. It is recommended to sample at least the top 10 cm of peat (excluding surface vegetation), while maintaining the peat structure. A corer with a diameter of 7 to 10 cm can be used for this purpose (Silva-Sánchez et al., 2019a). For calcareous mires, at least the top 15 cm should be sampled (excluding surface vegetation), again maintaining the peat structure. Analytical determinations are made by assessing the average of the upper 10-15 cm and the uppermost 5 cm of the core, excluding surface vegetation (Silva-Sánchez et al., 2019b).

Regarding the number of samples for all mire types, a minimum of three samples is recommended for undisturbed peat bogs with a maximum area of 10,000 $m^2$. For other cases, the following formula can be used: n=a/10,000 x 3, where a is the peat area in $m^2$ and n is the number of samples. Soil samples must be kept at 4-5ºC. Water samples should be taken at the mesotope level. Analysis of small pools on the peatland surface, as well as pore water analysis, may be carried out. Pore water sampling can be performed on an ad hoc basis by squeezing a section of peat or by spot sampling in the field. It is recommended to collect water samples after rainy days (Silva-Sánchez et al., 2019a, b).

In Hungary, sampling is carried out using fixed Permanent Monitoring Localities (PMLs), within which monitoring plots (MPs) are established. The MPs themselves are not fixed but their approximate location must be described. The size of a PML should be approximately 400 $m^2$ (20 x 20 m); if this is not feasible, it may follow the shape and morphology of the site. The monitoring plots (six plots of 0.5$m^2$) are placed along the diagonal of the PML, equidistant from one another. Most site-level information is recorded at the locality level. Within the PMLs, a phytocenological record is made, and the dominance of species is recorded as a percentage (Horváth et al., 2021).

The use of **remote sensing** as the primary data collection method remains limited among Member States, although various methodologies are currently being tested and explored. It is increasingly being tested for vegetation monitoring, hydrological change detection, peatland restoration monitoring, and mapping of inaccessible or extensive mire areas.

Sweden has maintained an established remote-sensing-based monitoring programme for all open wetlands since 2007. This system operates at the pixel level, flagging significant changes such as increased shrub or tree cover, or the effects of drainage. By 2017, every open wetland in Sweden had been evaluated, and in 2023, a second cycle of analysis commenced.

Monitoring of palsa mires (priority habitat 7320*) in Sweden is based on comprehensive mapping, random sampling of habitat areas, aerial photos, and detailed elevation models. The data are used to estimate changes in the total area and volume of palsas across the country (Wramner et al., 2023).

Norway has established a palsa monitoring programme (Hofgaard, 2004) based on transects laid along and across the fringe of the discontinuous permafrost zone at five selected sites. Collected climate data include air and soil temperature, precipitation, and snow depth. Habitat classification, morphology, vegetation structure, and human impact/land use data are also gathered at 5-year intervals. Sweden, Finland, and Norway cooperate on the joint monitoring of palsa mires.

In Finland, Jusilla et al. (2023) utilized Sentinel-2 satellite imagery and cloud computing to retrieve wetness information relevant for assessing the ecosystem condition of aapa mires (priority habitat 7310*) across the aapa mire zone. Two satellite-derived metrics – soil moisture index and the extent of water-saturated surfaces based on pixel-wise classification – were used to quantify monthly and interannual wetness variations.

This work produced the first comprehensive national-level representation of seasonal and interannual wetness variability and drought sensitivity of pristine aapa mire sites. The resulting methodology is applicable to aapa mires in other parts of Fennoscandia and enables extensive and harmonised monitoring of this priority habitat (Hofgaard, 2003).

Because aapa and palsa mires cover vast areas, remote sensing methods are necessary for effective monitoring, which should be applied systematically across the entire aapa and palsa mire zone.

The Annex I priority habitat type 7310* Aapa mires refers to minerotrophic patterned mire complexes, typically found in boreal regions, characterized by wetland mosaics of strings and flarks with diverse hydrology and vegetation. Natura 2000 site Hirvisuo, Finland. © Jozef Šibík

In 2021–2022, the Advances in Soil Information — MaaTi project produced the first comprehensive, high-resolution spatial dataset covering mires and dried peatlands throughout Finland. This database includes information on peatland site types and their fertility status according to the Finnish classification system, as well as drainage status and current land use.

The machine learning approach integrated satellite data, airborne laser scanning, geophysical data, and various GIS datasets to classify land cover status between 2000–2021. Mapping was conducted within the boundaries of existing peatland areas, adjacent field parcels, and peat extraction sites, based on a topographic database version published between 2005–2020 by the National Land Survey of Finland. The resulting national-scale map, presented in a 10-metre pixel raster resolution, contains three data layers: site types and peatland land use, fertility levels, and land cover of the peat extraction areas. The database is available for viewing and downloading[1] (Minasny et al., 2023).

**Monitoring frequency.** Most countries follow the monitoring frequency prescribed by Article 17 of the Habitats Directive, which is every six years. Some Member States apply a longer period (e.g., 12 years) to complete one monitoring cycle for each plot. In such cases, a larger number of monitoring plots is used, and plots are visited two or even three times during the cycle. As a result, not all plots are included in each six-year report, but are instead assessed cumulatively by the end of the cycle.

**Timing of sampling.** Monitoring is typically conducted during the vegetation season, with the recommended and commonly implemented period being from mid-June to the end of August. However, timing may vary among countries due to climatic differences, and within countries based on the phenological optimum of specific habitats. Some countries define precise sampling periods tailored to individual habitat types.

## 2.7 Other relevant methodologies

Hammerich et al. (2022) developed an indicator-based tool to assess mire-specific biodiversity in Northeast Germany. By evaluating biodiversity at the species, biocoenosis, and ecosystem levels – with each contributing up to 5 points – a composite score ranging from 0 (no mire-specific biodiversity) to 15 points (very high biodiversity) is obtained. The species-level score is based on the presence of mire-specific vascular plants and mosses. The biocenosis level incorporates the diversity o mire-specific and typical vegetation types and habitats (habitat diversity), as well as their position within the peatland network (habitat connectivity). The ecosystem level is evaluated based on the prevailing degree of topsoil peat degradation and on the soil moisture class (Tannenberg et al., 2024).

Remote sensing data should be actively used in inventories and monitoring. It enables the detection of mires sensitive to environmental change and supports the monitoring of habitat alterations, offering a new level of multi-scale ecosystem assessment.

In the United Kingdom, remote sensing options are being tested as lower-cost alternatives. Several studies have explored the remote assessment of peatland condition and degradation features using aerial photography (Scholefield et al., 2019), or combining it with LiDAR (Carless et al., 2019). Water table and surface elevation fluctuations have been monitored using interferometric synthetic aperture radar (InSAR) from satellite sources (Alshammari et al., 2018), a method that offers high-frequency monitoring of peat conditions and potential as a proxy for $CO_2$ emissions and removals (FAO, 2020).

At a broader scale, the condition of Scotland’s peatlands was recently modelled using a time series of satellite data (Artz et al., 2019). Sentinel-1 radar and Sentinel-2 spectral data are being evaluated for their potential to provide higher-resolution and repeatable assessments of

[1] https://gtkdata.gtk.fi/Turvevarojen_tilinpito/

peatland condition, particularly to support national greenhouse gas emissions reporting (Lindsay et al., 2019). However, none of these remote sensing techniques has yet been applied at a national scale (FAO, 2020).

### Citizen science

Eyes on the Bog (Lindsay et al., 2019) is a citizen science monitoring initiative for British peatlands. It engages the wider community in tracking the condition and long-term changes of peatlands and provides a robust, repeatable, and accessible methodology to harmonise basic data collection across a network of long-term monitoring sites.

The initiative uses cost-effective and simple techniques alongside modern technology to enable useful monitoring data to be collected by community employees or volunteers. This information can support management interventions and contribute to testing long-term climate predictions and assumptions about peatland condition and function. Data collected from independently established sites within the Eyes on the Bog network can be compiled in a standardised format via an open-access data hub. One such platform, PeatDataHub[2], is an emerging peatland-specific web application and database that facilitates the uploading and sharing of site metadata, datasets, files, and images from peatlands worldwide (FAO, 2020).

## 2.8 Conclusions

Various methodologies have been developed and implemented across the EU to evaluate the status of mire habitats. We have analysed more than 30 methodologies for assessing and monitoring the condition of mire habitat types from 18 Member States. These range from methods developed for a single mire habitat type, as in Poland (where several such methodologies exist), to approaches covering mire formation groups, such as in Spain and Ireland. In many cases, methodologies have been developed to cover all non-forest habitats, which remains the dominant approach.

An overall analysis of the variables used in these methodologies reveals a predominance of biotic variables, particularly species composition, including typical and indicator species. This element is present in all monitoring approaches. Assessments are based on lists of vascular plants and mosses considered typical for the habitat, with evaluations based on their presence or abundance. Plant indicators are commonly employed, often along a gradient from positive indicators (signifying good condition and ecological integrity) to negative indicators (reflecting disturbance, degradation, or ecological imbalance).

Another important group of variables widely used in mire monitoring includes influences and management, habitat structure, soil and water conditions, and habitat area. Among functional variables, the impact of drainage is one of the most frequently recorded across Member States. In most cases, qualitative data collection methods are used, and various evaluation procedures and scales are applied to estimate these variables.

Within structural variables, vertical structure is commonly assessed and includes distinct layers such as mosses, grasses and herbs, dwarf shrubs, shrubs, and trees. In contrast, horizontal structure and microtopography patterns – particularly relevant in bogs – are rarely considered in Member States' methodologies.

Permanent piezometric tubes or portable instruments for hydrological monitoring are seldom used and are mostly limited to restoration projects. Moreover, visual expert assessment of the

[2] https://peatdatahub.net/

hydrological regime in mires is inherently qualitative and may not be sufficient to capture key dynamics. As a result, a considerable data gap remains regarding the hydrological functioning of peatlands.

Soil and water chemical conditions are generally poorly assessed, likely due to the high cost and labour intensity of collecting such data across a large number of surveyed plots. As a result, several countries evaluate these characteristics indirectly and qualitatively, based on species composition. Among chemical variables, pH is the most frequently measured parameter across Member States.

Approaches to defining ranges and thresholds for assessing mire habitat condition vary significantly across EU Member States. While some countries — such as Poland, Germany, Spain, Belgium-Flanders, and Ireland — have developed clear thresholds for specific variables, others lack sufficient data or rely on broad concepts like “habitat degradation” without quantifiable benchmarks. In many cases, ordinal scales are used, but they don’t always align with clear condition categories (e.g. "good" vs. "bad").

Across Europe, documentation remains limited, and expert judgement is commonly used—even for quantitative variables. Most assessments rely heavily on vascular plant composition, which also serves as a proxy for abiotic conditions.

Although all Member States have developed detailed methodologies for defining and measuring variables used to assess the ‘structure and functions’ criterion, not all have established a clear aggregation methodology for the assessment at the local scale. Countries such as Spain, Poland and Ireland report distinct aggregation procedures specific to mire types. In contrast, the majority of Member States apply a common procedure either across all habitat types or across groups of habitats. In some cases, algorithms for aggregating condition assessments at the Natura 2000 site level are currently under development or being tested.

For aggregation at the biogeographical scale, most Member States follow the recommendations set out in the Article 17 reporting guidelines, which define how local condition assessments should be aggregated to produce an overall evaluation at the biogeographical level. According to these guidelines, "if 90% of the habitat area is considered to be 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’".

Some Member States apply the “one-out, all-out” approach (minimum aggregation, sensu Langhans et al., 2014) to weight indicators at both at local and biogeographical scales. Under this approach, a favourable conservation status requires that all important conditions for the specific mire habitat type are met at all assessed locations. Other Member States use various indices and descriptive statistics for aggregation at broader spatial scales.

The number of sample plots per habitat type and the methods used for selecting samples differ considerably between Member States. Overall, most Member States have applied at least a partly systematic selection approach based on the distribution, size, and characteristics of habitat types and/or other factors (Ellwanger et al., 2018). Based on our analysis, the number of sample plots in most Member States primarily depends on the frequency of occurrence of the habitat type.

The main approaches to selecting monitoring localities are: (1) expert-based selection; or (2) random or stratified random sampling. When plots are primarily selected using expert knowledge, criteria such as geographical distribution, size of habitat type occurrences, and variation within the habitat type are taken into account. Monitoring sites are also selected based on their degree of conservation, ranging from undisturbed mires to sites significantly impacted by various pressures. Majority Member States use permanent plots and include areas both within and outside the Natura 2000 network, applying standardised assessment schemes.

Most Member States implement sample-based monitoring schemes based on field mapping of individual occurrences of target habitats. These schemes vary considerably in the number and size of monitoring plots and in their sampling design and layout. The use of remote-sensing remains limited across most Member States, although Sweden and Finland are testing such techniques for monitoring aapa and palsa mires.

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

Preserving and restoring peatlands is essential for mitigating climate change and maintaining healthy ecosystems. However, due to ongoing pressures, many peatlands have been drained and converted to other land uses. These disturbed and degraded peatlands offer significant potential for restoration aimed at reducing carbon loss and safeguarding the ecological services provided by natural, undrained peatlands. Within Europe, the EU Habitats Directive recognises peatland ecosystems as priorities for conservation and restoration.

Nevertheless, differences in how EU Member States interpret and apply Article 11 of the Directive with regard to habitat monitoring have led to considerable variability in the proxies (variables), methods, metrics, and spatial representativeness employed. This inconsistency hinders the development of standardised procedures, limits the comparability of habitat assessments across Member States, and complicates data aggregation at the EU level. This section provides basic guidelines to support the harmonization of national approaches to monitoring the condition of mire habitats.

In addition, the new Nature Restoration Law, adopted in 2024, includes specific restoration targets for Europe’s degraded ecosystems. The plan aims to restore 30% of drained peatlands used for agriculture by 2030, ensuring that at least 25% of these are rewet. By 2040, the restoration target increases to 40%, with at least one-third of these being rewet. By 2050, 50% of these peatlands should be restored, again with at least one-third undergoing rewetting. The law states that EU countries should prioritise the restoration of habitats that are not in good condition and are located within Natura 2000 sites.

Reporting under the Nature Restoration Law must be carried out at least every six years and should be coordinated with the reporting cycle under Article 17 of Directive 92/43/EEC. As such, mandatory monitoring of peatland restoration is essential to ensure proper implementation and enforcement of the law.

This section aims to present a proposal for harmonisation to support further dialogue and alignment among relevant stakeholders.

## 3.1 Selection of condition variables, metrics and measurement methods

The unique characteristics of each component of mire biodiversity should be central to its assessment. All components – including specialist species, habitat conditions, and morphological heterogeneity – should be examined (Minayeva et al., 2017). To ensure effective monitoring, the selected variables must correspond to the key features and ecological processes that define habitat conditions.

**Condition variables** are quantitative metrics that describe specific characteristics of a habitat. These variables must have clear and unambiguous definitions, standardised measurement instructions, and well-defined units indicating the quantity or quality being measured. Examples include tree cover (%) or water turbidity. In this document, the following types of condition variables are included:

- **Essential variables:** These describe core characteristics of the habitat that reflect its quality or condition. They are selected based on intrinsic and instrumental relevance, validity, reliability, availability, simplicity, and compatibility. Essential variables should be assessed in all Member States using harmonised measurement procedures.

- **Recommended variables:** Optional, additional condition variables that may be measured where relevant and feasible. Their use is advised in particular contexts, depending on factors affecting habitats in different Member States.
- **Specific variables:** Condition variables that apply to particular habitat types within a broader group (e.g., tufa formation in calcareous fens or microrelief (e.g. hummocks and hollows in bogs). These should be measured only where relevant to the specific habitat.

**Descriptive or contextual variables:** These define environmental characteristics (e.g., climate, topography) that influence habitat condition. While not used directly in the aggregation of variables to determine overall habitat condition, they are useful for setting thresholds and interpreting the results of the assessment.

Despite the critical importance of mire ecosystems and the recognised need for their monitoring, there is considerable variability in the specific variables, metrics, and methodologies used across Member States. To harmonise the selection of mire condition variables, the following general principles should be applied:

- Variables should be selected based on their ecological significance and relevance to the specific characteristics and functions of the given mire habitat.
- Priority should be given to variables that are sensitive to environmental changes and management interventions, seving as early indicators of ecosystem condition.
- Standardized methods for data collection and analysis should be used to ensure comparability across Member States and biogeographical regions.
- Common metrics and units of measurement should be adopted to facilitate data integration and comparison.
- Variables should be monitored at appropriate spatial and temporal scales to capture both local and broader landscape-level changes.
- Selected variables should be realistically measurable within the constraints of available resources, including time, budget, and technical capacity.
- Variables should provide sufficient information to support decision-making on management or restoration, including the assessment whether the mire is in good condition. The collection of additional data beyond this purpose should be carefully considered, for example, where it supports research.
- Methods should be consistently applicable over time to support long-term monitoring and trend analysis.
- The final assessment of habitat condition, based on the selected variables, should be comparable across Member States, while accounting for local contextual factors such as biogeographical gradients, historical land use, and socio-economic conditions.

Having these principles in mind, we propose the following set of variables, grouped into abiotic, biotic and landscape categories (Table 12). This proposal builds on the main characteristics of the mire habitat group, described in section 1.2, and draws from information provided by Member States regarding habitat condition assessment, as well as habitat-specific literature.

The primary **physical abiotic characteristics** proposed for monitoring are hydrological conditions, as they play a critical role in the functioning of mires. Accordingly, hydrological conditions are identified as essential variables for monitoring. Hydrological conditions are monitored because they are not only a diagnostic indicator of current habitat condition, but also a predictor of long-term ecological integrity in mires. Without stable, saturated conditions, mire habitats degrade rapidly. Climatic variables, such as air temperature and precipitation, are considered important contextual variables, as they provide essential information for interpreting hydrological data and understanding broader ecosystem responses. For instance, ombrotrophic bogs are highly dependent on precipitation inputs. The degree of peat decomposition is proposed as a recommended variable. Elevated decomposition levels may indicate environmental alterations such as water table drawdown, increased temperatures, nutrient enrichment, or anthropogenic disturbances (e.g., drainage). These processes can disrupt the carbon balance of mires, potentially shifting them from net carbon sinks to net carbon sources, thereby contributing to atmospheric carbon enrichment and amplifying climate change feedbacks.

Key **chemical abiotic variables** for monitoring mires include pH and electrical conductivity (EC), both considered essential. These parameters can be easily and cost-effectively measured in situ using portable meters. However, due to their sensitivity to short-term fluctuations (e.g., precipitation events), continuous or frequent measurements are recommended to improve data reliability. While automated monitoring can provide high-resolution data, it may be limited by financial constraints.

pH reflects the acidity or alkalinity of a site. Deviations from habitat-specific ranges may signal disturbances such as pollution, nutrient runoff, or changes in hydrology. EC reflects dissolved ion concentrations and serves as a rapid, cost-effective proxy for hydrological status, habitat type, and potential disturbance in mires – supporting both early warning and long-term monitoring.

Nutrient availability (notably nitrogen and phosphorus) is recommended for detecting eutrophication and assessing ecosystem function. Elevated nutrient levels, often from anthropogenic sources, can disrupt species composition, accelerate decomposition, and reduce carbon storage. Nutrient analyses require laboratory processing of water or soil samples, entailing higher costs and methodological complexity. While direct measurements are essential in some cases to enable effective management interventions, in many situations the effort and cost may outweigh the benefits. An indirect assessment may be made based on the indicator values of plant species present at the site.

Among the **compositional state characteristics**, the presence and composition of characteristic and typical vascular plants and bryophytes are considered essential, as they reflect the typical structure and condition of mire habitats. Likewise, the presence of negative indicator species (e.g. harmful, alien, or invasive taxa) is also an essential variable, as it signals degradation and ecological imbalance. The use of functional indicator species related to soil moisture and water table depth is also classified as essential, as it provides valuable proxy information for key abiotic conditions. Other characteristics are recommended, including the abundance of characteristic and typical fauna species, presence of positive indicator species (reflecting high-quality conditions).

Essential **structural state characteristics** of mires include the composition and vertical structure of plant functional types — such as bryophytes, herbs, shrubs, trees, nitrogen indicators, and neophytes — measured as percentage cover of vegetation layers. These reflect key ecological processes and shifts in habitat condition. Specific structural characteristics include microtopographic features like hummocks and hollows, which are strong indicators of natural mire quality in bogs, and the presence of tufa formation, which signifies long-term hydrological and chemical stability specific to calcareous mires (habitat 7220*).

Essential **functional state characteristics** of mires include the type, extent, and intensity of disturbances affecting the habitat. These disturbances — whether natural or human-induced, such as drainage, peat extraction, fire, erosion, grazing, mowing, or the presence of infrastructure — can significantly alter the ecological function and integrity of mire ecosystems. Their assessment involves recording the presence or absence of pressures, the percentage of area affected, and classifying their impact as High, Medium, Low, or Unknown based on a standardized list. Monitoring disturbance patterns provides key insights into environmental stress and helps guide conservation and restoration actions.

The essential **landscape characteristic** for mires is the total surface area of the target habitat, as changes in habitat extent directly indicate loss, degradation, or restoration success. Recommended characteristics include habitat connectivity or fragmentation, which affects ecological resilience, species movement, and hydrological function, and land use in the catchment area, which helps identify external pressures such as drainage, agriculture, or forestry that may impact mire condition at the landscape scale.

Alkaline fens (7230).
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**Table 12. Proposals for condition variables for assessing and monitoring mires**

The variables are included in the types recognized in the SEEA EA methodology. Metrics may show several options

| Description | Condition variables | Importance | Metrics | Application | Standardised measurement procedures |
|---|---|---|---|---|---|
| **1. Abiotic characteristics** | | | | | |
| **1.1 Physical state characteristics** | | | | | |
| **Hydrological conditions** | **Water table level and its fluctuations** | A high and stable water table indicates peat formation and the maintenance of anaerobic conditions essential for mires. | Mean, minimum, and maximum water table depth (cm) | Essential | In constructed monitoring wells, both the groundwater level and the elevation of the well head must be determined. Several methods may be used:<br>**Manual measurements using dipwells or dedicated gauges**. Water levels can be recorded manually in representative microhabitats using simple dipwells or mechanical (acoustic) and electric designed for groundwater measurements. Measurements should be taken during stable seasonal conditions and must always be accompanied by relevant metadata to support interpretation.<br>**Automated logging using data loggers barometric pressure sensors.** While continuous monitoring systems (including water level and water chemistry loggers) offer high-resolution data, their installation is not feasible in all mire areas. Therefore, automated logging should be prioritised for reference sites and other high-value areas - particularly those at risk where timely mitigation may be needed. |
| **Climatic conditions** | **Air temperature and precipitation** | Climatic variables serve as explanatory factors for interpreting hydrological monitoring data. Long-term trends provide evidence of climate change and its potential impacts on mires. | Mean, minimum, and maximum air temperature (°C); total precipitation (mm) over a defined period | Contextual | Automated Weather Stations or direct measurements at the site may be used. Precipitation, particularly relevant for ombrotrophic systems, can be measured using rain gauges - either manually read or equipped with automatic logging. Where available, climatic data may also be retrieved from national meteorological networks or modelled datasets. |

| Description | Condition variables | Importance | Metrics | Application | Standardised measurement procedures |
|---|---|---|---|---|---|
| **Carbon stock** | **Peat depth** | Depth itself is mainly important as a proxy for stored carbon and for defining peatland status. It is a slow-changing, long-term attribute. Depth data are also critical for prioritising conservation investments where the greatest ecological and climate benefits can be achieved. | Mean, min, max peat depth (m);<br>Depth distribution across site;<br>Estimated total peat volume (ha × mean depth). | Recommended | Field coring: Use a peat corer (e.g. Russian corer, Wardenaar corer) to measure depth to mineral substrate at representative points.<br>Probing: Use a calibrated metal or fiberglass rod (peat probe) pushed to refusal (mineral contact).<br>Survey design: Measurements along transects or grid depending on mire size and heterogeneity.<br>GPS referencing: Each point georeferenced for mapping.<br>Data processing: Generate depth maps to visualise spatial variation.<br>It's highly valuable for carbon stock estimation, long-term resilience assessment, and habitat definition, but it doesn't need to be included in every routine monitoring cycle in Member States. |
| **Peat decomposition** | **Degree of peat decomposition** | The degree of peat decomposition reflects past and present hydrological conditions, nutrient status, and vegetation history of the peatland. | Degree of peat decomposition according to the von Post scale (H1 – H10) | Recommended | Sampling tools such as a peat auger or corer should be used to collect samples from different depths.<br>The colour and structure of the peat should be observed, including identification of visible plant remains and their state of preservation. A rapid field assessment technique involves squeezing a handful of peat to assess the colour and quantity of water released. |
| **1.2 Chemical state characteristics** | | | | | |
| **Water and soil chemistry** | **pH** | pH indicates acidity or alkalinity. Significant deviations from the natural range may signal pollution, nutrient runoff, or other external disturbances. | Measured pH value | Essential | pH is typically measured using a pH meter or pH-sensitive electrodes in the field. Seasonal and spatial variability within the mire should be taken into account. The method is low-cost and straightforward to implement. |
| **Water and soil chemistry** | **Electrical conductivity (EC)** | EC reflects the concentration of dissolved ions (salts and minerals) in water, serving as rapid indicator of water quality and potential disturbances. | Electrical conductivity (μS/cm) | Essential | Electrical conductivity (EC) is typically measured in situ using portable EC meters or multiparameter water quality probes. The method is cost-effective and straightforward to apply. Interpretation thresholds:<br>Low EC (0-200 μS/cm): Typical of pristine, rain-fed bogs with low mineral content, indicating minimal groundwater or surface runoff influence.<br>Moderate EC (200-800 μS/cm): Common in fens and transitional mires with some groundwater influence and higher nutrient levels.<br>High EC (>800 μS/cm): Suggests substantial groundwater input, mineral-rich conditions, or potential pollution sources. |

| Description | Condition variables | Importance | Metrics | Application | Standardised measurement procedures |
|---|---|---|---|---|---|
| **Water and soil chemistry** | **Nutrient availability (nitrogen and phosphorus)** | Nutrient availability helps detect pollution sources and eutrophication, which can alter species composition and mire functioning. | Concentration of total nitrogen (including nitrate $NO_3$ and ammonium $NH_4$, and total phosphorus or phosphates ($PO_4$); all in mg/l | Recommended | Nutrient concentrations (e.g., nitrogen and phosphorus) are analysed in standardised laboratory procedures using water or soil samples collected in the field. This method provides valuable insights for establishing baseline nutrient levels in near-natural mires and for detecting inputs in sites affected by agriculture, forestry, drainage, or atmospheric deposition. Nutrient analysis is also recommended in restoration contexts – both prior to and following interventions – to monitor nutrient dynamics and assess restoration outcomes. However, this approach involves higher costs, resource demands, and complexity in data interpretation, especially in the context of specific mire habitat types. |
| **2. Abiotic characteristics** | | | | | |
| **2.1 Compositional state characteristics** | | | | | |
| **Characteristic and typical species** | **Species composition of vascular plants and bryophytes (from standardised lists)** | Characteristic and typical species are commonly or consistently found in a given habitat type and represent its typical composition. | Number and composition of characteristic and typical species | Essential | Species that are commonly or consistently found in a given habitat type and represent its typical composition. Species list of characteristic and typical vascular plants and mosses should be established for each specific habitat type and region, and used in all assessments of mire biodiversity. Recording overall species composition – ideally through permanent monitoring plots – supports the detection of long-term ecological changes and site-specific trends. |
| **Mire-specific fauna** | **Occurrence of characteristic and typical fauna species (from standardised lists)** | Mire-specific fauna indicates favourable ecological status and habitat integrity. | Number of characteristic and typical species | Recommended | Standardized methods are typically used for sampling and data collection for selected groups of fauna species. Target groups should be chosen based on their relevance to mire ecosystems. Methods may include transect surveys, pitfall traps, or acoustic monitoring, depending on the taxa of interest. |
| **Indicator species** | **Presence of positive indicator species** | Positive indicators species indicate high-quality and well-functioning habitat conditions. | Number of positive indicator species | Recommended | List of positive indicator species (vascular plants and mosses, but also lichens cyanobacteria, algae, diatoms, liverworts etc.) should be established according to the specific habitat type and region. These lists are in assessments to evaluate mire biodiversity and ecological quality. |
| **Indicator species** | **Presence of negative indicator species** | Negative indicator species signal negative impacts on habitat quality and functioning. | Number of harmful, alien, or invasive species | Essential | List of negative indicator species should be established for each habitat and region. The number of harmful, alien, or invasive species is recorded as an indicator of habitat disturbance and nutrient enrichment. |

| Description | Condition variables | Importance | Metrics | Application | Standardised measurement procedures |
|---|---|---|---|---|---|
| **eDNA metabarcoding for microbial diversity** | **Microbial community composition** | Microbial communities respond rapidly to environmental changes, providing early warning signs. | | Recommended | Microbial communities can be assessed through analysis of alpha diversity, which reflects species richness at the local scale. These methods are scientifically valuable but often time consuming and costly. |
| **Functional indicators** | **Presence of functional indicator species for soil moisture and water table depth** | The composition of functional indicator species can reflect long-term hydrological conditions and may serve as a proxy for essential abiotic variables. | Unweighted mean of indicator values | Essential | Hájek et al. (2020) developed updated ecological indicator values for soil moisture and water table depth, ranging from 1 to 12 (species optimum), with additional measures for ecological valence (minimum, maximum, and range). These values are based on both statistical and expert-based analyses of species co-occurrence data and can be used to infer long-term hydrological conditions from vegetation composition. |
| **2.2 Structural state characteristics** | | | | | |
| **Plant functional types** | **Cover of plant functional types (bryophytes, herb layer, shrubs, trees, nitrogen indicators, neophytes)** | Changes in the vertical structure of plant functional types can indicate broader environmental shifts and habitat transformation. | Percentage cover (%) of vegetation layers (e.g., bryophytes, herbs, shrubs, trees) | Essential | Structural elements such as plant layers (e.g., bryophytes, herb layer, shrubs, trees) are assessed visually in the field and interpreted using orthophoto maps. Cover is expressed as a percentage of the sampling unit. |
| **Microtopogra-phy** | **Presence and extent of microtopographic features (e.g., hummocks and hollows)** | Microrelief is a strong indicator of mire quality and natural microtopography patterns. | Percentage cover of microforms (%) | Specific for bogs | Microrelief is a highly informative indicator of mire quality. It can be characterized by assessing topographic variability and classifying conceptual microforms (e.g., pools, hollows, lawns, hummocks), which reflect functional gradients from wet to dry conditions. Microtopography can be quantified by estimating the relative cover (%) of these microforms. Advances in technology now enable large-scale assessment of microtopography using high-resolution elevation data derived from remote sensing techniques (e.g. LiDAR or UAV-based photogrammetry) |

| | | | | | |
|---|---|---|---|---|---|
| **Microtopography** | **Presence and activity of tufa formation** | The presence of tufa deposits indicates long-term stability in water chemistry and flow conditions, characteristic of calcareous mires. | Percentage cover of microforms (%) | Specific for habitat 7220* | To assess it, conduct a visual estimation of the percentage cover of tufa-forming microstructures such as encrusted mosses, stone-like accretions, and miniature travertine terraces. Within each monitoring plot or subplot, classify cover into predefined percentage classes (e.g. 0%, <10%, 10–25%, 25–50%, >50%). In addition, record qualitative features such as surface texture, colour, and hardness of the deposits to help distinguish actively forming tufa from older, relict structures. These observations provide insight into the current activity status of calcium carbonate precipitation and the ecological functioning of the habitat. |
| **Description** | **Condition variables** | **Importance** | **Metrics** | **Application** | **Standardised measurement procedures** |
| **2.3 Functional state characteristics** | | | | | |
| **Disturbance** | **Footprint, number and intensity of pressures** | Disturbances – whether natural or anthropogenic – can significantly affect the structure and function of mires and serve as indicators of environmental stress. | Presence/absence and % of area affected by human activity (e.g. drainage, peat cutting, fire, erosion, anthropogenic structures, grazing, mowing, restoration). | Essential | Disturbances are recorded through visual field surveys, mapping, remote sensing, and GIS. Various disturbance types may be identified, with their significance evaluated based on frequency, duration, intensity, and type of impact. Developing an objective, repeatable, and cost-effective monitoring approach remains a challenge.<br>Impact can be graded as High, Medium, Low, or Unknown based on a standardised list of pressures. |
| **3. Landscape/Seascape characteristics** | | | | | |
| **Total surface area covered by the target mire habitat** | **Habitat patch** | Changes in total habitat extent reflect habitat loss or gain over time. These may indicate degradation or restoration success. | Total area in hectares (ha) | Essential | Monitoring methods include GIS analysis of aerial or satellite imagery, remote sensing (e.g., multispectral or radar data), field mapping with GPS, and comparison with historical maps and records.<br>Assessment is typically conducted every 6 years. |
| **Connectivity/ Fragmentation within the mire complex or monitoring unit** | **Habitat connectivity or fragmentation** | Fragmentation reduces habitat resilience and species dispersal, increases vulnerability to edge effects, invasive species, and hydrological disruption, and compromises long-term ecological integrity. | Area in hectares per quare kilometre (ha/km$^2$); percentage (%) of area directly affected by human activity | Recommended | Assessment of the presence and percentage cover of anthropogenic structures. Comparisons of spatial imagery over time support the evaluation of habitat fragmentation and connectivity. Approaches may include quantitative and qualitative methods, supported by expert judgement. |

| | | | | | |
|---|---|---|---|---|---|
| **Land use impact in the catchment area** | **Land use type and intensity in the catchment area** | Land use in the catchment area provides critical information for assessing landscape-scale pressures affecting mire condition. | Percentage (%) of catchment area affected by land-use activities (e.g., drainage, agriculture, forestry) with potential impacts on mire hydrology and ecological functioning | Recommended | Assessment includes the percentage cover of different land use categories (e.g., agriculture, forestry, drainage infrastructure, urban areas, peat extraction); the distance or proximity of intensive land use to the mire margin (e.g., buffer zone width); a qualitative evaluation of land use pressure (low / moderate / high); and the number or extent of drainage ditches and water abstraction points. |

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

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

Reference levels should be defined consistently across different variables within a given ecosystem type, and for the same variable across different ecosystem types. This ensures that derived indicators are compatible and comparable, and that their aggregation is ecologically meaningful (United Nations, 2021).

Reference levels are typically defined with upper and lower values reflecting the endpoints of a condition variable's range, which can then be used in re-scaling. For instance, the highest value may represent a natural state, while the lowest value may represent a degraded state where ecosystem processes fall below the threshold required to maintain function (Keith et al., 2013, in United Nations, 2021). For example, pH values in freshwater ecosystems clearly indicate whether biological life can be sustained, while soil nutrient enrichment beyond a certain threshold can lead to the loss of sensitive species.

Establishing reference values and thresholds is essential for determining whether habitats are in good condition or have become degraded. Reference values represent the desired state of an ecosystem, typically reflecting intact or minimally disturbed conditions. These values serve as benchmarks for assessing habitat condition.

These guidelines do not aim to prescribe specific threshold values. Rather, they outline the main criteria and provide guidance for establishing reference values that support the determination of good or not-good condition, while accounting for the ecological variability of habitats across their range.

With regard to the variables, the harmonisation of reference values and thresholds should consider a set of **common requirements**:

- For a given habitat, the final assessment of its condition and trend over time – based on the reference values and thresholds of the variables characterising the habitat – should be equivalent across Member States (MSs), after accounting for the contextual factors specific to each MS (e.g., climate).
- Thresholds, limits, and reference values should be tested using sufficiently robust datasets that represent the full range of habitat conditions, from degraded to high-quality sites.
- Thresholds must account for the natural variability of habitats across their range. Consequently, different threshold or reference values for the same habitat type may be appropriate in different MSs or in different regions within a single MS.
- Establishing reference values requires information external to the evaluated site, which can provide insight into the condition of the habitat and be translated into variable values that characterise that condition.
- Reference values should meet the criteria of validity (ecological relevance), robustness (reliability), transparency, and applicability (Czúcz et al., 2021; Jakobsson et al., 2020).

- Each MS should provide a clear, justified, and comprehensible description of the methodology used to establish threshold and reference values for each variable.
- The methodologies should be designed for regular evaluation and improvement, based on the best available scientific knowledge. Any modifications made – and their implications for past monitoring data – must be communicated transparently.
- A reference library and indicator thresholds should be developed for different habitat types across regions, taking into account their ecological characteristics and natural variability.
- Joint training or guidance on setting threshold and reference values should be offered to experts from the different MSs in order to achieve ensure harmonised approaches.

Several approaches have been recognised for estimating reference values to assess habitat condition (Stoddard et al., 2006; Jakobsson et al., 2020; Keith et al., 2020). These can be broadly synthesised into six categories: (1) absolute biophysical boundaries, (2) comparison to reference empirical cases - i.e., areas or communities considered to be in good condition, (3) comparison to undisturbed cases, (4) modelling and extrapolation of variable-condition relationships, (5) statistical assessments, and (6) expert judgement.

All approaches should be grounded in scientific literature. Methods that use values from a single baseline year as a reference for good condition are not recommended, as the selected year may not reflect favourable conditions, and historical data may be unreliable or incomplete (Jakobsson et al., 2020). The use of historical period (e.g., pre-industrial) as a reference state, as proposed by Stoddard et al. (2006) and Keith (2020) aligns with the baseline approach but also overlaps with comparisons to undisturbed cases (see below). If conditions during a specific baseline year are well documented as favourable, they may be useful for trend analyses. Likewise, where historical pristine conditions are clearly documented, they may serve as valid reference states under the undisturbed comparison approach.

### Absolute biophysical boundaries

These refer to situations in which observed values of variables exceed the physical and chemical limits (e.g., pH, bare soil cover, critical loads for eutrophication or acidification) or biotic limits (e.g., presence of alien species) that define the habitat. When such limits are exceeded, the habitat cannot be in good condition (Jakobsson et al., 2020). These thresholds therefore indicate negative impacts on the favourable condition of the habitat.

- Advantages: This approach provides robust and transparent criteria that are clearly linked to the ecological integrity of the habitat.
- Disadvantages: It is applicable to a limited number of variables, typically those with direct negative impacts on habitat condition.

### Comparison to reference areas

#### Cases considered to be in good condition

This approach is based on identifying areas or communities considered to be in good condition (Stoddard et al., 2006; Jakobsson et al., 2020; Keith et al., 2020). These serve as reference cases from which the reference values can be derived. Therefore, their careful selection – and the availability of a sufficient number of such cases – is essential for ensuring the reliability of the reference value estimates (Soranno et al., 2011). While this method may appear straightforward, it is often limited by the scarcity of suitable sites, especially in landscapes that have been historically modified.

- Advantages: Providing that sufficient data from high-quality cases are available, this approach offers empirical validity and reliability by directly linking variable values to habitat condition.
- Disadvantages: Methodological challenges arise due to the difficulty of identifying a sufficient number of suitable reference sites in historically altered environments.

### Cases with a natural disturbance regime

This approach is closely related to the previous one, based on the assumption that most human-induced disturbances reduce habitat quality. This assumption is generally valid in human-modified landscapes and can be linked to historical reference conditions when human pressures were less pronounced (Stoddard, 2006). However, disturbances that are part of a natural disturbance regime may actually indicate naturalness and thus good habitat condition. In fact, a certain level of disturbance can be beneficial, supporting microhabitat formation, enhancing biodiversity, and promoting regeneration of habitat-characteristic species (Keith et al., 2020).

Historical reference criteria may include the absence of human intervention or management, as found in “primary” forests (sensu Sabatini et al., 2017), and are often directly connected to climax communities such as old-growth or primeval forests (Wirth et al., 2009; Burrascano et al., 2013; Buchwald, 2005), which are typically assumed to be in good condition. However, in regions with long-standing anthropogenic pressure, it may be difficult to identify unaltered or naturally disturbed habitats for certain types (Keith et al., 2020). Additionally, defining the undisturbed state based on a relatively short time period may overlook disturbance legacies that persist over longer timescales (Alfaro-Sánchez et al., 2019).

- Advantages: This approach provides transparent and empirically grounded criteria for defining reference conditions and can benefit from large-scale information on disturbance and land-use history.
- Disadvantages: The assumption that any disturbance reduces habitat quality may not always be valid. Moreover, identifying sufficient undisturbed or naturally disturbed reference areas can be challenging for some habitat types.

## Modelling the relationships between variables and condition

This approach assumes a relationship between variable values and habitat condition. When determining threshold and reference values, models that describe these relationships share a conceptual basis with methodologies based on dose-response curves. Such models assume that certain cases of good condition correlate with specific levels of a condition variable.

The advantage of modelling is that it allows reference values to be inferred where empirical examples of good condition or undisturbed condition are lacking. In these situations, information from known empirical examples can be extrapolated to other contexts, such as locations along a climatic gradient.

Various modelling procedures are available. Functional relationships – linear, saturated, or humped – can be applied (Stoddard et al., 2006; Jakobsson et al., 2020). For instance, deadwood volume in pristine forests can be modelled along productivity gradients to establish reference values in climatic conditions where unaltered forests no longer exist (Jakobsson et al., 2020). Correlative climate niche models can also be used to estimate the suitability of species sets (i.e., variables that characterise the habitat) at different points along the climatic gradient (Jakobsson et al., 2020).

Although these approaches offer a functional basis for establishing reference values, they involve several assumptions that often require expert judgement. It is also possible to create models in which condition is inferred from variables other than the condition variable itself – for example, biodiversity-related condition variables may be inferred from pollution levels. However, this approach should be used with caution to avoid tautological inferences involving variables that reflect pressures.

- Advantages: Modelling approaches are flexible, transparent, and encompass a variety of procedures based on functional relationships between variables and condition (validity), drawing on scientific knowledge from multiple disciplines. They can also be applied to obtain reference values when empirical examples of good or undisturbed condition are lacking.
- Disadvantages: The information available to build models is often insufficient or unreliable for many variables. Outputs are highly sensitive to the chosen modelling procedure and underlying assumptions, and expert judgement is ultimately required at multiple stages of the modelling process.

### Statistical assessments

This approach is based on quantitative data from databases, such as habitat inventories, which report the distribution of variables within a given habitat. It assumes that higher values of certain variables correspond to good condition when a positive relationship exists, and vice versa. For such variables, high percentile values or confidence intervals (e.g., 95%, Jakobsson et al., 2020), or differences from the maximum observed values (Storch et al., 2018), may be used.

For variables with a negative impact on habitat condition, low (e.g., 5%) or minimum values are applied, while for variables that show a hump-shaped (non-linear) relationship with condition – peaking at intermediate values (e.g., gap occurrence, browsing) – a combination of high and low percentiles may be used.

This approach is particularly suited to variables obtainable from forest inventories (Storch, 2018; Pescador et al., 2022), and is useful when empirical examples of good condition are lacking. However, it may provide limited insight into the state of habitats that are in poor condition throughout the entire assessed territory. In other words, this approach is not directly based on reference situations of good condition, but on statistical inferences subject to the constraints of the sampling used to build the reference database.

- Advantages: This approach can be applied with reasonable ease by users with statistical training. It is transparent, replicable, and minimally subjective.
- Disadvantages: The existence of appropriate, quantitative datasets representing the reference state is essential for this method. Its reliability depends on the distribution of condition classes (from bad to good) in the dataset and on how well this distribution corresponds to empirical situations of good condition. As a result, it may lead to under- or overestimation of good condition and may be less reliable for habitats that are poorly represented in the dataset.

### Expert judgement

Setting of reference values and thresholds based on expert judgement is common practice, particularly where other sources of information are lacking – for instance, in certain non-abundant habitats where experts have developed empirical knowledge of habitat condition.

However, this approach is often criticised for its limited transparency, and the level of expertise may be insufficient in some cases. For this reason, it is sometimes considered a last-resort option for many variables.

Nonetheless, for certain variables – such as assemblages of characteristic species, successional stages, the presence of microhabitats, or regeneration characteristics – expert judgement may be appropriate for establishing thresholds and reference values. In other cases, it can also serve as a complement to other approaches.

In all situations, it is advisable to apply expert judgement through protocols based on consensus and consultation with multiple experts of comparable experience. This should include clear procedures (e.g., standardised questionnaires) and transparent documentation of how conclusions were reached (Stoddard et al., 2006). A further limitation is the lack of available experts for certain habitats, which can hamper the correct application of this approach.

- Advantages: This approach is easy to apply and is commonly used.
- Disadvantages: It entails a high degree of subjectivity and low transparency, which limits replicability and reliability. Its use may also be constrained by the scarcity of suitable experts for particular habitats and Member States.

Table 13 provides an overview of the approaches used to establish thresholds and reference values for the proposed condition variables intended for harmonisation. These approaches are drawn from methodologies applied by Member States and documented in the literature. Given the uncertainties involved in setting reference levels, a combination of approaches is generally recommended to improve reliability. The approaches described are not mutually exclusive, and are often applied in combination. For example, expert judgement is typically required when defining reference cases for good condition or when making modelling decisions about the relationship between variables and condition. Similarly, modelling-based approaches can complement those based on empirical cases of good or undisturbed condition and may also be integrated with statistical methods.

Habitat condition assessments are based on determining whether the variables used indicate good or not good condition. However, it is common practice to define more than two categories for each variable – e.g., good, medium, and bad – as observed in the analysis of methodologies used by MSs. The criteria for assigning these condition categories vary depending on the characteristics of each variable. For example, categorical variables may involve thresholds such as “no alien species allowed”, while quantitative variables may follow linear or non-linear relationships with condition (Jakobsson et al., 2020).

This classification of variable values – whether quantitative or categorical – into condition categories (e.g., good, not good; or good, medium, bad) corresponds to the scaling process needed for joint evaluation through aggregation procedures, as described in the following section. Condition categories can be translated into numerical values (e.g., good = 2, medium = 1, bad = 0). Alternatively, where quantitative values for the variables are available, these can be directly standardised for use in aggregation.

Owing to the different metrics and magnitudes used for the variables that characterise habitats, the values obtained from their measurement require some form of standardisation – e.g., through re-scaling – in order to build indicators that combine multiple variables. (see further details in Section 3.3. on Aggregation).

Thresholds, limits and reference values must be tested against sufficiently broad data sets, covering the full range of habitat conditions – from degraded to high-quality examples. A reference library should be established, and indicator thresholds identified across mire types and regions.

**Table 13. Overview of approaches used to establish thresholds and reference values for determining favourable condition, applicable to the proposed variables for assessing the condition of mire habitats**

Dark grey indicates referred or commonly applied criteria; light grey denotes additional criteria. E: Essential, S: Specific, R: Recommended

| Description | Biophysical boundaries | Reference areas | Modelling | Statistical assessments | Expert judgement |
|---|---|---|---|---|---|
| **1. Abiotic characteristics** | | | | | |
| **1.1 Physical state characteristics** | | | | | |
| Water table level and its fluctuations | | | | | |
| Air temperature and precipitation | | | | | |
| Degree of peat decomposition | | | | | |
| **1.2 Chemical state characteristics** | | | | | |
| pH | | | | | |
| Electrical conductivity (EC) | | | | | |
| Nutrient availability (N & P) | | | | | |
| **2. Biotic characteristics** | | | | | |
| **2.1 Compositional state characteristics** | | | | | |
| Species composition of vascular plants and bryophytes | | | | | |
| Abundance and population density of characteristic and typical fauna species | | | | | |
| Presence of positive indicator species | | | | | |
| Presence of negative indicator species | | | | | |
| Microbial community composition | | | | | |
| Presence of functional indicator species for soil moisture and water table depth | | | | | |
| **2.2 Structural state characteristics** | | | | | |
| Cover of plant functional types (bryophytes, herb layer, shrubs, trees, nitrogen indicators, neophytes) | | | | | |

| Description | Biophysical boundaries | Reference areas | Modelling | Statistical assessments | Expert judgement |
|---|---|---|---|---|---|
| Presence and extent of microtopographic features | | | | | |
| Presence and activity of tufa formation | | | | | |
| **2.3 Functional state characteristics** | | | | | |
| Footprint, number and intensity of pressures | | | | | |
| **3. Landscape/Seascape characteristics** | | | | | |
| Habitat extent | | | | | |
| Habitat connectivity or fragmentation | | | | | |
| Land use type and intensity in the catchment area | | | | | |

## 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 for combining these partial assessments into an overall evaluation has been widely discussed within the scientific community, as it can significantly influence the final outcome. 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).

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.

### 3.1.1 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., addition, arithmetic mean, geometric mean).
Further information on aggregation approaches and methods is provided below.

**Minimum aggregation, or the one-out, all-out rule**

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

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 and averaging approaches

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.

### 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.

### 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 5).

**Figure 5. Example of normalisation by rescaling the values obtained for the 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)

### 3.1.2 Proposal for the aggregation of measured variables

A quantitative aggregation method should be applied to integrate all essential and specific variables measured to assess the habitat condition. The method should be applied consistently across the habitat range in order to obtain comparable results. The main steps for aggregation are described below.

#### 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

The aggregated value is then calculated by the aggregation of the normalised values of the variables. 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

According to the latest reporting guidelines, if more than 25 % of the habitat type area within the assessed biogeographical region is considered unfavourable condition (i.e., not in good condition), the status of Structure and Function is classified unfavourable-bad. However, no specific numerical criteria are provided for distinguishing favourable or unfavourable-inadequate status.

Ideally, the entire area of a habitat type should be in good condition for Structure and Function to be considered favourable. In practice, however, this is rarely achievable. It may therefore be acceptable for a proportion of the habitat type area in not-good condition, while still assessing Structure and Function as favourable.

An indicative threshold of 90 % of the habitat type area in good condition is recommended as a benchmark for concluding favourable Structure and Function. If a Member State applies a different value, this should be explicitly stated and justified. The indicative threshold may be adapted according to the rarity or abundance of the habitat type – e.g., closer to 100% for rare habitat types with restricted distribution.

## 3.5 Guidelines on general sampling methods and protocols

Harmonised monitoring protocols are essential for assessing habitat condition consistently across Europe. Such protocols should provide standardised methods for data collection, analysis, and interpretation to ensure comparability over time and across biogeographical regions. This section presents recommendations for sampling designs and monitoring protocols specifically applicable to mires.

The status of mire habitat types can be monitored using field-based inventories, remote sensing (RS) methods, or an integrated approach combining both. Modern monitoring increasingly relies on the synergy between these methods, where RS data help assess spatial patterns and change dynamics, while field observations validate and enrich the interpretation, especially for ecological detail not detectable via RS.

Despite significant advancements, the large-scale application of RS methodologies remains limited, mainly due to difficulties in upscaling models across diverse regions. Moreover, there is a broad agreement that RS cannot substitute for certain in-situ observations – such as the presence and abundance of typical species – which require direct field assessment.

Therefore, field surveys remain the primary and irreplaceable component of habitat condition assessment. Sampling designs should aim to be representative, repeatable, and cost-effective, covering the ecological variability of the habitat type. Where possible, a stratified random sampling approach is recommended, and all methods should include clear protocols for data quality control, documentation, and metadata reporting.

**Baseline mapping for mires**

Baseline mapping is particularly useful when establishing new monitoring schemes, as it provides a spatial reference for stratifying sampling across the ecological variability of mires. It is especially valuable in heterogeneous sites with distinct hydrological zones or microtopography, and supports the detection of habitat changes over time. Baseline maps are also important for planning restoration or management interventions, defining monitoring units and boundaries, and validating remote sensing outputs. In cases where existing habitat documentation is outdated, incomplete, or missing, baseline mapping ensures a reliable starting point for consistent long-term assessment.

A baseline survey is essential for effective site-level monitoring of mires, as it provides the foundation for stratifying sampling efforts and ensuring representativeness across the ecological variability of the site. This typically involves mapping the extent and structure of the mire to inform the selection of appropriate monitoring methods and sampling design (Natural England, 2015).

For mire habitats, baseline mapping should consider not only vegetation patterns but also key features such as hydrological zones, microtopography (e.g. hummocks and hollows), and disturbance gradients, which are critical for interpreting habitat condition.

Depending on monitoring objectives, site size, and logistical feasibility, several mapping approaches can be used:

- Wall-to-wall mapping is suitable for comprehensive spatial coverage, particularly in uniform or accessible sites, and ensures full representation of habitat variation.
- Mapping of selected sampling polygons supports stratified sampling, capturing ecological gradients such as wetness or successional stage, while being more practical in large or remote mires.
- For small or homogenous sites, or when using fixed plots, detailed mapping may be unnecessary.
- In regions where detailed mapping is not feasible, habitat or hydrological modelling can serve as an alternative to support stratification and monitoring design, particularly when combined with limited ground-truthing.

To ensure reliable results, baseline mapping should be carried out by experienced surveyors and, if properly conducted, only needs to be performed once.

### Groundwater monitoring in mires

Monitoring groundwater levels is essential for understanding the hydrological functioning of mires, as the depth and dynamics of the water table are key drivers of vegetation composition, peat formation, and overall habitat condition. While water table levels naturally vary across different mire types (e.g. bogs vs. fens), general hydrological patterns can still be identified and used to evaluate site condition and changes over time, especially in response to restoration measures.

The number and placement of monitoring wells (piezometers) should be based on site size, hydrological complexity, and the objectives of the monitoring or restoration programme. It is recommended to install a grid or targeted transects of monitoring wells to capture spatial variation and enable a robust characterisation of groundwater conditions. Wells should be placed to reflect known or expected gradients (e.g. wet-dry zones, inflow/outflow areas, or management units).

Once installed, regular measurement of water levels is required — ideally at intervals that capture seasonal variability and responses to rainfall or management actions. In addition to water level, monitoring of basic water chemistry parameters such as pH, specific conductivity, and where relevant, nutrient concentrations, provides further insight into water quality and its influence on mire ecological processes.

When groundwater monitoring in mires is too costly or unrealistic, a practical approach involves focusing on key representative areas, using low-cost methods like manual piezometers, and reducing measurement frequency to key seasonal periods. Proxy indicators such as vegetation composition and surface conditions can provide additional insights into water regime. Remote sensing and hydrological modelling may also help detect moisture changes over time.

### Sampling approaches

Monitoring the condition of mire habitats should be conducted within a network of permanent monitoring plots, established to measure site-level habitat characteristics, vegetation composition, and structural conditions. Two methods are recommended:

**Relevé Sampling Method.** This method involves selecting a representative plot (or quadrat), located within a visually homogeneous patch of mire vegetation corresponding to a single habitat type. Relevé plots can vary in size, depending on the habitat type and study objectives.

Smaller plots are typically used for assessing vegetation composition (full vegetation relevé), while larger plots are used for recording structural variables. This approach is informed by species-area curves and aims to balance two key factors: the accuracy of cover estimation and the proportion of habitat sampled within the survey area.

**Line Transect Method.** This method involves placing a straight line (transect) through the habitat. Transect length can vary (e.g., 10 m to 100 m), depending on the size of the monitoring area. At regular intervals along the transect (e.g., every 10 or 20 m), plant species or structural features that directly intersect the line are recorded. This method can also be used to monitor environmental variables such as water depth. For example, in some sites, a small area of high-quality vegetation may be found in the centre of the mire, with vegetation quality gradually declining toward the edges. In such cases, surveying at fixed intervals along transects radiating outward from the centre may provide useful information (Natural England, 2015).

In practice, the relevé and transect methods can be combined to maximise data quality. For example, relevé plots may be positioned along a transect to capture both species composition and environmental gradients. Regardless of method, ensuring repeatability, spatial representativeness, and consistency in observation protocols is critical for reliable long-term monitoring of mire habitats.

### Remote sensing methods

Remote-sensing techniques are effective for monitoring peatland condition, particularly in areas subject to intense human pressures over large spatial scales. They can be used to detect drainage patterns, extent of vegetation inundation, surface moisture content, and relative water table position (Minasny et al., 2023).

**Light detection and ranging (LiDAR).** When collected at high point densities, LiDAR data allow for accurate and detailed topographical analysis. From post-processed data, it is possible to extract precise vegetation heights, canopy structure, and ground elevation. The ability of LiDAR to penetrate vegetation improves the accuracy of Digital Terrain Model (DTM) generation, which is essential for detecting and quantifying changes in surface features. Full waveform LiDAR is especially valuable in peatlands, as it can measure both vegetation structure and ground surface geometry with high precision (Korpela et al., 2020).

**Synthetic Aperture Radar (SAR).** There is a growing trend in using Synthetic Aperture Radar (SAR) and optical time series to assess water table depth. SAR can penetrate into the top few centimetres of the soil, providing information that is not accessible through optical data. SAR backscatter has been used to estimate surface soil moisture and has shown correlations with water table depth time series in peatlands and wetlands.

Unlike optical sensors, SAR can penetrate cloud cover – an important advantage in the wet climates where peatlands are typically found. The SAR sensor onboard the two Sentinel-1 satellites offer strong potential for monitoring soil moisture fluctuations, due to its frequent revisit intervals and high spatial resolution (down to 10 m), particularly in high–latitude regions where many peatlands are located (Lees at al., 2021).

### Monitoring frequency

Article 17 of the Habitats Directive requires a maximum monitoring interval of six years. However, this period may be approached flexibly, depending on the resources available in each Member State. Not all plots, and not all variables need to be surveyed every six years.

Member States may choose to establish a large number of monitoring sites, selecting only a subset to be surveyed every season. This rotating approach allows a sufficient number of plots to be fully monitored within each six-year cycle.

Data collection should be timed during the optimal vegetation period, considering local climate and phenology.

## 3.6 Selecting monitoring localities and sampling design

The selection of sampling localities – along with the sample size (number of plots) and power – is essential to ensure that the results of assessment and monitoring are representative of each habitat type at the biogeographical scale.

**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. 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 three 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.

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.

**Sample size and distribution:**

- The number of localities/transects etc. should be sufficient to provide a statistically robust sample size. This ensures that the data collected can be generalized to the entire habitat type within the region.
- Statistical methods such as stratified random sampling are often used 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 benthos, infauna, mobile species and other ecological indicators. The distribution and number of sampling stations depend on the variability and size of the habitat patch. Sampling areas (plots, transects) are laid out considering the existing main ecological gradients, e.g., exposure to waves/currents/tides, depth, sediment characteristics.

**Replication and randomization:**

- Replication of sampling units within each locality and randomization of sampling plots location help to reduce bias and increase the reliability of the data.
- Randomized plot locations ensure that the sampling captures the natural variability within the habitat.

## 3.7 Use of available data sources, open data bases, new technologies and modelling

The **Global Peatland Database (GPD)**[3] is a project of the International Mire Conservation Group, hosted and maintained by the Greifswald Mire Centre. The GPD collates and integrates data on the location, extent, and drainage status of peatlands and organic soils worldwide, covering 268 individual countries and regions. The database includes analogue and GIS maps, reports, field observations, photographs, and is supported by the Peatland and Nature Conservation International Library (PeNCIL). The GPD regularly produces integrative analyses, including biennial global overviews of peatland status and emissions. It provides science-based, policy-relevant spatial information to support climate change mitigation and adaptation, biodiversity conservation and restoration, and sustainable land use planning.

The **Global Peatlands Initiative**[4] includes partners such as the Food and Agriculture Organisation of the United Nations (FAO), the UN Framework Convention on Climate Change (UNFCCC), and the International Union for the Conservation of Nature (IUCN). At the global level, the Initiative provides an up-to-date overall assessment of the status of peatlands and their significance in the global carbon cycle and national economies. It emphasises the role of peatlands in achieving global climate commitments, as outlined in the Paris Agreement.

**Using of remote sensing data.** The basic components of all digital mapping studies follow a common framework: the collection of data from field surveys and ancillary sources, followed by mapping supported by Earth observation data through remote sensing. Satellite remote sensing is a powerful tool for regional mapping of biophysical variables relevant to peatland carbon research. It enables data collection over large areas and extended time periods, which are often impractical or unfeasible through field observations alone. Remote sensing can be used to (1) classify plant functional types, including their greenness and phenology; (2) detect saturated and inundated soils, as well as open water; and (3) measure permafrost features and other environmental parameters such as surface temperature, snow cover, and topography (McLaughlin & Webster, 2013).

The following are key benefits of using remote sensing platforms in peatland monitoring (Abdelmajeed & Juszczak, 2024):

- Remote sensing – particularly satellite-based – enables coverage of inaccessible terrain, allowing the exploration and monitoring of peatland areas that are difficult to reach by foot or traditional field methods.

[3] https://greifswaldmoor.de/global-peatland-database-en.html
[4] https://globalpeatlands.org/

- It allows measurements and observations to be made without direct contact with the studied environment, ensuring that the physical properties of the peatland are not altered during data collection.
- Remote sensing facilitates the upscaling of point-scale measurements to larger spatial extents, such as slopes, basins, valleys, or even entire mountain ranges. This capability supports a broader understanding of peatland dynamics and patterns across varying landscapes.
- Radar data, commonly used in remote sensing, offer weather independence. Data can be acquired regardless of weather conditions, enabling consistent monitoring and analysis over time.
- Remote sensing enables the collection of complete and continuous data records over time from specific locations. These longitudinal datasets help reveal temporal patterns, changes, and trends in peatland characteristics and dynamics.
- A variety of sensors can be used in remote sensing, each capable of measuring specific physical properties of peatlands. This multi-sensor approach allows for a comprehensive understanding of factors such as vegetation dynamics, hydrological conditions, and subsurface characteristics;
- Remote sensing data archives offer access to historical datasets, enabling researchers to analyse changes in peatlands over time. By utilising these archives, valuable insights can be gained into long-term trends and transformations.

The limitations associated with remote sensing in peatland research include the following:

- Mapping peatland ecological conditions at an appropriate scale can be challenging. Peatlands often appear visually homogeneous at moderate spatial resolutions (e.g., MODIS satellite imagery), but reveal high structural and ecological complexity at finer resolutions (e.g., in drone or airborne imagery).
- The reflectance spectra of peatland vegetation – particularly Sphagnum mosses – can change when desiccated, making it difficult to accurately identify species or assess moisture content using spectral satellite data.
- A relatively small number of studies have so far demonstrated the utility of hyperspectral satellite and UAV-based remote sensing for peatland research. This highlights the need for further investigation to establish its effectiveness and reliability in this context.
- Acquiring remote sensing data with very high spatial resolution can be costly, which may limit its accessibility and practical application in peatland research and management.
- Remote sensing data with very high spatial resolution typically covers a narrow swath, which limits the spatial extent of peatland areas that can be assessed. This constraint may hinder the comprehensive monitoring of larger peatland regions.
- In operational contexts involving large volumes of data, automated algorithms are essential for peatland analysis. However, most existing algorithms are tailored to optical data, and there remains a lack of studies focused on radar-based approaches.
- Field validation data remain limited, particularly in inaccessible peatland areas. This hampers the verification of remote sensing-based analyses and reduces confidence in the results.
- There is also a lack of quantitative error assessment methods for both manual and automated remote sensing analyses of peatlands. Developing robust measures to assess accuracy and uncertainty is essential to ensure both the reliability and validity of the derived information.

# 4. Guidelines to assess fragmentation at appropriate scales

The degree of fragmentation is recognised by the European Commission as an important indicator of habitat condition: ”for a habitat to be considered 'favourable', fragmentation or other conditions are not impacting significantly on ecological processes” (European Commission, 2017).

Patch size, spatial arrangement, and heterogeneity are critical to a wide range of ecological, biogeochemical, and hydrological processes within individual mires. Mire cover and shape influence the formation of large mire complexes, while fragmentation and patch abundance are largely determined by topography (Ehnvall et al., 2024).

Fragmentation – the breaking up of mires into smaller, isolated patches – poses a major threat to their ecological integrity, biodiversity, and functioning. It is often driven by human activities such as drainage, land conversion, infrastructure development, and the effects of climate change. Lawrence et al. (2021) define fragmentation as a landscape-scale process involving: (a) a reduction in total habitat area, (b) an increase in the number of habitat patches, and (c) a decrease in the size of individual patches.

Mire fragmentation is a significant ecological driven by both human activities and natural processes. It contributes to habitat loss, biodiversity decline, altered hydrology, and reduced carbon storage capacity. Monitoring fragmentation using remote sensing, GIS tools, and field surveys is essential for understanding its impacts. Assessing mire fragmentation involves analysing the extent to which these ecosystems have been broken into smaller, isolated patches, and evaluating the consequences of this fragmentation for their ecological integrity and functioning. The following approach is proposed for assessing mire fragmentation:

1. **Delineate the study area and objectives.** Identify the mire types present in the study area (e.g., bogs, fens), as different types may respond differently to fragmentation. Clearly define the assessment objectives — whether focusing on the extent of fragmentation, its impacts on biodiversity, hydrology, carbon storage, or other ecological functions.
2. **Data collection.** Acquire high-resolution, up-to-date data using satellite imagery, aerial photographs, or LiDAR. Collect historical data to analyse changes over time and identify trends in fragmentation. Conduct ground-truthing to validate remote sensing outputs and assess the condition of remaining mire patches. Gather complementary field data on vegetation, water levels, and other ecological variables potentially affected by fragmentation. Use Geographic Information System (GIS) tools to analyse land use, land cover, and hydrological features surrounding the mires.
3. **Mapping and characterisation of mires.** Use the collected data to accurately delineate the boundaries of mire patches. Identify and describe individual patches, noting their size, shape, and degree of isolation. Classify patches according to their ecological condition, vegetation type, and hydrological status.
4. **Fragmentation metrics.** Habitat fragmentation can be assessed statically, by characterising fragmentation at a single point in time, or dynamically, by comparing fragmentation indices derived from past and current data. The metrics used to assess fragmentation can be grouped into three categories (Hargis et al., 1998; Wang et al., 2014):
   - **Patch-level metrics.** These metrics describe the characteristics of individual habitat patches. Common patch-level metrics include:

   - Patch area – the size of individual mire patches; smaller patches are generally more vulnerable to degradation and edge effects.
   - Patch perimeter – the total length of the patch boundary.
   - Edge density – the length of patch edge per unit area.
   - Shape Metrics:
     - Shape index – compares the patch perimeter to that of a circle with the same area; higher values indicate more complex shapes.
     - Fractal dimension – measures the complexity of the patch boundary, with higher values reflecting increased irregularity.

- **Class-level metrics**. These metrics assess fragmentation at the landscape level. They provide a broader perspective by considering the overall distribution and configuration of habitat patches within a given area. Common class-level metrics include:
   - Landscape shape index – measures the complexity of the landscape configuration; higher values indicate a more fragmented and irregular landscape.
   - Fractal dimension – quantifies the complexity of the overall landscape pattern; higher values suggest greater irregularity and fragmentation.
   - Patch density – indicates the number of patches per unit area; higher density reflects increased fragmentation.
   - Patch size distribution – describes the range and frequency of patch sizes across the landscape, showing whether the area is dominated by a few large patches or many small ones.
   - Edge density – represents the total length of all patch edges per unit area; higher values point to increased edge effects and fragmentation.

- **Connectivity metrics.** These metrics evaluate the degree of ecological connectivity between habitat patches. They include:
   - Mean patch isolation – the average distance between patches; higher values indicate greater spatial isolation and reduced connectivity.
   - Connectivity index – measures the degree of functional connectivity between patches; higher values reflect stronger linkages across the landscape.

## 5. Ecological impact assessment

- Assess species richness and composition in fragmented vs. continuous mire patches. Fragmentation often results in a species loss, particularly among those sensitive to habitat size and isolation. Increased fragmentation may also heighten the sensitivity of patches to hydrological variations, affecting peat decomposition and $CO_2$ emissions.
- Evaluate hydrological changes caused by fragmentation, such as altered water flow patterns and shifts in water table levels.

## 6. Trend analysis

- Compare current fragmentation levels with historical data to identify temporal trends. Determine whether fragmentation is increasing, decreasing, or stabilising.

## 7. Impact of human activities

- Assess the role of human activities such as agriculture, forestry, urbanisation, and infrastructure development in driving mire fragmentation.
- Evaluate the effects of drainage systems, pollution, and other anthropogenic pressures on the fragmentation and degradation of mire ecosystems.

## 8. Conservation and management implications

- Identify priority areas for conservation, restoration, or connectivity enhancement based on fragmentation assessment.
- Determine where restoration efforts could reconnect fragmented patches, improve habitat quality, or re-establish hydrological processes.
- Develop policy recommendations to mitigate further fragmentation and protect remaining mire ecosystems. Implement conservation strategies at the landscape scale to maintain and enhance connectivity.

# 5. Next steps to address future needs

These guidelines offer a proposal for moving towards harmonized procedures in the assessment and monitoring of mire habitats, based on existing methodologies and with a view to promote common approaches that can produce comparable results. To ensure that habitat condition assessments are comparable across countries, it is essential to define 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. While some methodologies already include some physical and soil chemical variables, additional measurements, such as soil organic carbon, should be prioritised. These data are crucial to understanding the impacts of climate change and anthropogenic pressures.

A possible next step is to promote the harmonisation of monitoring methodologies across all EU Member States to ensure consistency and comparability of mire habitat assessments.

- 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 the existing 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 implementation of the aggregation of results at the biogeographical region level;
- Promote harmonised methods for the use of typical species: Typical species provide a practical way to evaluate habitat status, reflecting specific ecological conditions. 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.

The current proposal should be viewed as a starting point and may be adapted where more suitable alternatives are identified based on national experience or ecological requirements.

Further research is also needed to advance mire habitat mapping and monitoring using new technologies. The most promising research avenues include:

- Make high-resolution open-source data available to guide and facilitate conservation, rewetting, restoration, and sustainable use. Support peatland mapping, monitoring, and research to improve and verify national greenhouse gas inventories, biodiversity reporting, and carbon standards (Declaration of the "Power to the Peatlands" conference 19-21 September 2023, Antwerp).
- Integrate AI and machine learning with remote sensing data, and develop algorithms to automate habitat mapping (e.g., Mikula et al., 2023), detect habitat changes, and support species identification from remote sensing data.
- Expand the use of Unmanned Aerial Vehicles (UAVs) and sensors to collect high-resolution data on vegetation structure and soil properties (de Castro et al., 2021).

- Improved eDNA extraction and analysis techniques offer new opportunities to monitor hard-to-detect taxa such as invertebrates, fungi, and bacteria. In mires, eDNA-based microbial diversity is a promising complementary tool for assessing habitat condition and serves as an early-warning indicator of ecological change. However, it requires specialised expertise, robust methods, and careful interpretation. When integrated into broader monitoring frameworks, eDNA can enhance biodiversity assessments and support more effective peatland conservation.

Coordinating the monitoring and reporting requirements of the Nature Restoration Law with those of the Habitats Directive is crucial for the effective restoration and conservation of peatlands in the EU. By aligning reporting cycles, harmonising monitoring protocols, integrating data collection and management systems, and fostering stakeholder collaboration, it is possible to establish a robust framework that supports the objectives of both directives. This coordinated approach will strengthen the ability to track progress, ensure compliance, and ultimately promote the sustainable management of Europe’s peatland ecosystems.

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# Annex - National methodologies used

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