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

Heath and Scrubs

ATECMA

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Contents

Glossary and definitions

Habitats

Natural habitats: 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, which, in turn, underpin the integrity of the habitat. 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 ecosystem 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: species that characterise, are used to define the habitat type, can be dominant or accompanying species, and are used to identify the habitat.

Dominant species: in a vegetation community are those with the highest abundance or biomass, effectively shaping the community's structure.

Typical species*:* the term ‘typical species’ in the Habitats Directive is linked to the definition of favourable conservation status (Article 1(e)). Typical species are used to assess habitat condition and, in this context, include species that are good indicators of favourable habitat quality and species that are sensitive to changes in habitat condition (‘early warning indicator species’).

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 an 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 based on their relevance, validity and reliability and should be assessed in all MSs following equivalent measurement procedures.
- **Recommended variables:** are optional, additional, complementary condition variables that may be measured when relevant; they complement the essential variables and can help improve the assessment, understanding, or interpretation of the overall results.
- **Specific variables**: are condition variables that should be measured in some particular habitat types or habitat sub-groups; they 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 and help characterise the habitat in a specific location, define relevant thresholds for the condition variables, and interpret the assessment results. These variables are not included in the aggregation of the measured variables to determine the habitat condition.

Reference levels and thresholds: these are defined as the values (or ranges) of the variables 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

UAV: unmanned aerial vehicle

Executive summary

The Heaths and Scrubs habitats covered in these guidelines encompass diverse vegetation types, including heathlands, shrublands, and sclerophyllous scrublands, characterized by low woody plants adapted to nutrient-poor soils and varied climatic conditions. The Directive classifies these habitats within Groups 4 (Heaths and scrubland of temperate zones) and 5 (Mediterranean scrubland), with some representation in Group 1 (Coastal habitats and halophytic vegetation). Their ecological characterization highlights their responses to environmental controls, including soil properties (e.g., pH, texture, nutrient availability), bioclimatic factors (e.g., temperature, precipitation), and topographically driven microhabitat heterogeneity. These habitats exhibit complex successional dynamics, functioning as permanent communities in nutrient-poor soils or transitional stages toward forested ecosystems under favourable conditions. Adaptive traits, such as sclerophyllous foliage, fire resilience, and mycorrhizal associations, enable these systems to persist while supporting biodiversity, endemic species, and critical ecosystem services such as carbon sequestration, soil stabilization, and water regulation.

An analysis of existing methodologies across EU Member States reveals significant variability in assessing and monitoring these habitats. Compositional characteristics such as species diversity and characteristic species are widely used and often well-defined, providing valuable insights into habitat health and biodiversity. Structural measures, including vegetation height, horizontal cover, and habitat heterogeneity, are also standard, but thresholds for interpreting these metrics are often inconsistent or absent. Functional variables, such as carbon sequestration, primary productivity, and biotic interactions, remain underrepresented in most methodologies, limiting the ability to comprehensively assess ecosystem processes and services. Landscape-level metrics, including fragmentation, connectivity, and spatial heterogeneity, are inconsistently applied, often relying on localized assessments rather than integrated, large-scale evaluations.

We propose a set of variables for monitoring Heaths and Scrubs, categorized into abiotic (e.g., soil moisture, pH), biotic (e.g., species richness, indicator, and invasive species), structural (e.g., vegetation height, cover, and heterogeneity), functional (e.g., primary productivity, successional stages, and fire regimes), and landscape metrics (e.g., patch size, connectivity, edge effects). 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.

The guidelines outline several priority areas for future efforts, including closing gaps in functional metrics such as carbon dynamics and phenology, integrating climate change impacts into monitoring protocols to enhance resilience, and fostering collaboration and capacity-building among Member States. Strengthening knowledge exchange, technology sharing, and coordinated efforts is critical to fostering an inclusive, collective approach to conservation. Aligning methodologies with EU biodiversity policies, particularly the Nature Restoration Regulation, will be vital in achieving restoration and conservation goals. These forward-looking steps aim to enhance the effectiveness of monitoring and conservation strategies, ensuring that Heaths and Scrubs habitats continue to deliver their ecological and socio-economic benefits amidst growing environmental pressures.

1. Definition and ecological characterisation

1.1 Definition and interpretation of habitats covered

Heaths and scrubs habitats comprise a wide range of vegetation formations characterised by low woody plants with varying degrees of density and canopy cover. Defining such habitats is complex because vegetation types range from open to denser scrublands, each with distinct characteristics that shape their ecological responses to environmental controls. The characteristics of vegetation that dominate these habitats differ markedly in terms of plant density, species composition, soil properties, and vegetation structure, with these variations influenced by environmental conditions and disturbance regimes. They are characterised primarily by shrubs and, in some cases, young or small trees, generally under 5 meters in height (Mortimer et al., 2000; Leuschner & Ellenberg, 2017).

Three main types can be differentiated by their structure and ecological characteristics: heathlands, shrublands, and scrublands. **Heathlands** are characterised by low-growing, dwarf shrub vegetation that thrives in acidic, nutrient-poor soils, common in temperate, arctic, or Mediterranean climates. **Shrublands** include sparse vegetation types dominated by tall shrubs. Finally, **scrublands** are characterised by a denser arrangement, with a continuous or near-continuous canopy of shrubs and small trees growing close together, leading to overlapping layers of vegetation. The ecological ranges of shrublands and scrublands are wide in terms of soil conditions and climate, although they are predominant in areas with a Mediterranean climate. Among the different scrub forms, krummholz represents a distinctive, stunted growth pattern of shrubs and small trees adapted to harsh, high-altitude climates (Holtmeier & Geographie, 1981; Albertsen et al., 2014). Overall, the structural characteristics of Heath and Scrub habitats play a pivotal role in determining their composition and function, creating diverse niches that support specialised flora and fauna adapted to various levels of canopy cover and different soil conditions.

Heaths and Scrubs exhibit complex non-directional successional dynamics shaped by natural ecological processes and human pressures. These habitats play varied roles in ecological succession, functioning as early, intermediate, or climax communities based on environmental context and disturbance patterns. In some cases, they persist as permanent communities under particular soil conditions, such as the nutrient-poor, acidic soils in heathlands, or drought-prone, low-nutrient soils in Mediterranean scrublands (Mortimer et al., 2000; Medail & Quezel, 1997). Other limiting substrates include gypsum (Mota et al. 2011, Escudero et al. 2015), dolomite (Mota et al. 2021), and serpentine soils (Hidalgo-Triana et al. 2023). Scrubs often act as transitional communities in the successional shift from open habitats to forests, eventually giving way to trees when disturbances are absent (Day et al., 2003).

Human activities, including land-use change, agricultural expansion, and fire suppression, significantly affect the successional dynamics of these habitats. Traditional management practices, such as controlled burning, rotational grazing, or selective clearing, can help maintain these ecosystems in early or intermediate successional stages, thereby promoting habitat heterogeneity and biodiversity. In Heathlands (Press et al., 1998) and Mediterranean scrublands (Medail & Quezel, 1997; Medáil, 2022), regular fire—whether natural or human-induced—is vital for maintaining open sclerophyllous vegetation, as many species are adapted to periodic fires and can quickly resprout or regenerate. However, shifts in management conditions, such as reduced grazing and controlled burning, can trigger natural succession processes that favour the establishment of larger shrubs and trees, transforming open scrubs into more closed, wooded areas (Rosa-García, 2013), thereby reducing habitat availability for species adapted to open conditions. Such changes may contribute to declines in biodiversity, as certain ground-nesting birds, insects, and small mammals lose essential habitat resources (Ombashi et al., 2023).

Heaths and Scrubs are often considered less conservation-relevant than mature forest formations; however, protecting them is essential to maintaining Europe's ecological heritage. They hold huge conservation interest because they support unique biodiversity and provide critical ecosystem services. They often harbor specialised species adapted to particular environmental conditions and usually restricted to specific geographical distributions (endemic), including ground-nesting birds, diverse invertebrates, and numerous endemic plants. This fact is particularly relevant in the Mediterranean region, where extraordinary biodiversity and a high degree of endemism are found (Comes 2004, Guarino et al. 2020). Conservation measures for shrubland-dependent animal species may include reducing tree density, promoting chamaephyte growth, and encouraging low-level transhumance grazing to maintain suitable habitat structure. In terms of ecosystem services, they mainly contribute to soil stabilisation, water cycle regulation, carbon storage (Weeb, 1998), and pollination. These habitats are particularly vulnerable to anthropogenic pressures, including climate change, urban expansion, invasive species, and intensive agriculture, particularly those that occur over large areas in the coastal regions (Mendoza-Fernández et al. 2015a) and Mediterranean islands (Medáil, 2022).

In the Habitats Directive (92/43/EEC), Heaths and Scrubs are mainly categorised within Groups 4 (Heaths and scrubland of temperate zones) and 5 (Mediterranean scrubland), with some representation in Group 1 (Coastal habitats and halophytic vegetation). There are 24 habitats under heaths, shrublands, and sclerophyllous scrubs listed in the EUNIS habitat interpretation manual. These can be further divided into two subgroups based on ecological condition, biogeography, and species composition. Subgroup 1, consisting of Heaths and Shrublands prevalent in the Atlantic, Alpine, Boreal, and Arctic regions, encompasses various temperate heath and scrub types. Subgroup 2 (Sclerophyllous scrub), commonly found in the Mediterranean and Macaronesian regions, includes habitats of community interest dominated by shrubs or small woody shrubs, sclerophyllous nanophanerophytes or chamaephytes, and sometimes leafless shrubs. Some habitat types are exclusive to specific Member States (MS). An example is the *Cistus palhinus* formations on maritime wet heaths (habitat type 5140) found only in Portugal. Similarly, the Dry Atlantic coastal heaths with *Erica vagans* (habitat type 4040) are limited to Spain and France.

Subgroup 1 (Heathlands and Shrublands) are ecosystems typically dominated by small shrubs of *Erica* spp., and other plants that thrive in acidic and nutrient-poor soils. These ecosystems are common in humid, cool climates, mountains, and coastal areas. Soil acidity and nutrient deficiency are fundamental to thriving. These characteristics limit the growth of larger plants and favour species adapted to these conditions. Plants in heathlands have specific adaptations, such as small, needle-like leaves, wax or hair coverings, and extensive root systems, to survive in acidic, nutrient-poor soils. Associations with mycorrhizae are also common, facilitating nutrient uptake. Periodic fires are an important component of their functioning, removing accumulated biomass, releasing nutrients, and promoting the germination of fire-adapted species. Heathlands with the highest richness of floristic composition are located in the northwestern Iberian Peninsula, benefiting from a humid, oceanic climate (Loidi et al. 2010). Factors such as temperature and summer droughts also significantly influence the distribution and richness of these habitats, as is the case with the dry heaths in the south of the Iberian Peninsula (Ojeda et al. 1995). This subgroup also includes mainly natural, partly semi-natural communities of dwarf-shrub heaths dominated by ericaceous species (*Empetraceae, Ericaceae, Vacciniaceae*), krummholz (*Pinus mugo*), Salix spp., and *Juniperus communis*, commonly found in high elevation, Arctic, and subarctic regions (Press et al., 1998; Ganthaler & Mayr, 2021).

Subgroup 2 (Sclerophyllous scrub) includes formations dominated by shrubs or small woody shrubs, sclerophyllous nanophanerophytes or chamaephytes, and sometimes leafless shrubs (e.g., *Retama* spp*, Genista* spp.). They can be linked to forest formations or permanent communities when harsh climatic conditions, specific edaphic conditions, or adverse geomorphological conditions prevail. In many cases, they characterise biotopes with highly stressful conditions limiting the development of other vegetation types. Examples include mountain scrubs, thermophilic scrublands, pre-desert shrublands, gypsum shrublands, halophilic and sub-halophilic shrublands. This group comprises habitats from Group 5 and part of Group 1 (linked to gypsum outcrops, salt marshes, and subsaline soils or with some anthropogenic alteration in arid and semi-arid environments).

Heathlands and scrub habitats can be logically divided into two subgroups.

Subgroup 1, Heaths and shrublands, includes the following diverse types:

Northern Atlantic wet heaths with *Erica tetralix* (4010) are characterised by humid, peaty conditions and are found in Atlantic regions, excluding blanket bogs. **Temperate Atlantic wet heaths with *Erica ciliaris* and *Erica tetralix* (4020)** thrive in moist heaths within temperate oceanic climates, typically on semi-peaty or dried-out soils, with surface minerals in peaty soils (hydromor). **European Dry Heaths (4030)** appear on sandy, nutrient-poor soils in moister Atlantic and subatlantic climates and are commonly found in low mountains and plains across Western and Central Europe. **Dry Atlantic coastal heaths with *Erica vagans* (4040)** are well-drained coastal heathlands in temperate areas, featuring specific plant species such as *Erica vagans* and *Ulex europaeus*.

Endemic Macaronesian heaths (4050) are dominated by heather (*Erica* spp.) and bayberry (*Myrica faya*), found on the windward slopes of the western and central Canary Islands, as well as on the summits of Madeira and the Azores. These formations thrive in the same climatic conditions as cloud or laurel forests, situated on mid-altitude slopes where trade winds provide humidity through rain or mist. They are characterised by high environmental humidity, except for some dry ridge heaths in summer. They are often located on andosol-type soils with compact substrates, such as steep slopes and ridges. These heath habitats are found in humid climates in mountainous or coastal areas.

Alpine and Boreal Heaths (4060) are small dwarf-shrub formations in the alpine zones of Eurasia, dominated by ericaceous species, dwarf junipers, brooms, or greenweeds; *Dryas* heaths of the British Isles and Scandinavia belong here as well. **Bushes with *Pinus mugo* and *Rhododendron hirsutum* (*Mugo-Rhododendretum hirsuti*) (4070)** represent scrub and krummholz formations in the inner and Eastern Alps, the Swiss Jura, the eastern greater Hercynian ranges, the Carpathians, the Apennines, and the mountains of the Balkan Peninsula, primarily consisting of *Pinus mugo* and *Rhododendron* species. **Sub-Arctic Willow Scrub (4080)** includes willow formations in subarctic and boreo-alpine regions, often near streams.

Subcontinental peri-Pannonic scrub (40A0) refers to low deciduous scrub in the Pannonian basin and surrounding regions, forming a mosaic with steppe grasslands and forest elements. **Rhodope *Potentilla fruticosa* thickets (40B0)** are dense thickets dominated by *Potentilla fruticosa*, which is endemic to the Rhodope mountains. Lastly, **Ponto-Sarmatic deciduous**

thickets (40C0) are found in the wooded steppe zone of the Pontic and Sarmatic regions, including several endemic species.

In summary, habitat types 4020, 4030, and 4040 are distributed at lower altitudes, generally develop on nutrient-poor soils, and are characterised by the absence of tree cover, with sun-loving species dominant. In contrast, habitat types 4060, 4070, 4080, and 4090 are situated around or above the tree line, showcasing a greater diversity of species often endemic to high mountains. Habitat type 4050 exhibits intermediate characteristics between the two basic heathland types associated with laurel forests and can appear as either heath or pre-forest formations in the island Macaronesian region. The common characteristics of 40A0, 40B0, and 40C0 include low deciduous scrub that forms mosaics with adjacent steppe grasslands and forest elements, highlighting a diversity of habitats within specific regions, such as the Pannonian basin, the Rhodope Mountains, and the Pontic and Sarmatic regions. The influence of the wooded steppe affects the structure and composition.

Subgroup 2, Sclerophyllous scrub (matorral), includes various habitat types:

1420 Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornetea fruticosi*) and **Halo-nitrophilous scrubs (matorrals) – *Pegano-Salsoletea* (1430)** are typical of dry soils under arid climates and may feature taller, denser bushes. **Mediterranean salt steppes – *Limonietalia* (1510)** are characterized by scattered scrub formations rich in perennial plants such as *Limonium* spp. and esparto grass, occupying Mediterranean coasts and Iberian salt basins, where soils are temporarily saline and subject to extreme summer drying, leading to the formation of salt efflorescence. **Iberian Gypsum Steppes – *Gypsophiletalia* (1520)** are found in the Iberian Peninsula, located on gypsum-rich soils and typically open, featuring numerous gypsophilous species.

1520 Iberian Gypsum Steppes
© Javier Cabello

Endemic Oro-Mediterranean Heaths with Gorse (4090) consist of cushion-shaped primary shrubs in the high Mediterranean and Irano-Turanian mountains. This habitat is fundamentally Mediterranean, present in five of the six states within the Mediterranean biogeographical region, with notable extensions in the Macaronesian region. **Stable Xero-thermophilous Formations with *Buxus sempervirens – Berberidion* p.p. (5110)** are shrub formations found on calcareous rock slopes dominated by *Buxus sempervirens* in the hill and montane level. **Mountain *Cytisus purgans* Formations (5120)** are low-growing or cushion-shaped formations dominated by brooms (*Cytisus purgans* s.l.), existing above the forest limit in siliceous mountains and often bordering various forest types, being replaced at higher altitudes by high mountain pastures. ***Juniperus communis* Formations (5130)** are open shrub formations dominated by common juniper, resilient to varying precipitation levels and harsh continental climates, which may be accompanied by *Calluna vulgaris* or *Cytisus scoparius* in situations of more or less acidic soil, but also occur on calcareous soils accompanied by dry calcareous grassland vegetation. These formations can replace surrounding forests. ***Cistus palhinhae* Formations on Maritime Wet Heaths (5140)** feature low scrub formations rich in endemics, predominantly dominated by *Cistus palhinhae*, and can be found in the Algarve region of southwestern Portugal.

Arborescent matorral with *Juniperus* spp. (5210) is typical of Mediterranean and sub-Mediterranean regions, characterized by sclerophyllous shrublands with junipers and tree-like savin. These are seral stages of different types of natural forests, generally acting as a pre-forest shrub stage. **Arborescent matorral with *Zyziphus* (5220)** represents deciduous, pre-desert scrublands typical of the semi-arid southeastern Iberian Peninsula and other arid regions of Mediterranean islands like Cyprus, Sicily, and Lampedusa. They are thorny, intricate communities with small, primarily deciduous leaves that thrive in the dry season. These shrublands are notable for the abundance of tropical or subtropical taxa or remnants of past climatic conditions, often with a distribution primarily in North Africa. **Arborescent matorral with *Laurus nobilis* (5230)** consists of humid thickets dominated by laurel, usually serving as the border and initial stage of oak and eutrophic mixed oak groves, particularly in karstified and thermal areas. They can form permanent communities in some locations, like rocky ledges and lapiaces. ***Laurus nobilis* thickets (5310)** are linked to particular edaphic and/or microclimatic conditions that distinguish habitat 5230 from habitat 5310 and vice versa. The only reliable character is the structure of the community, mainly the difference between shrubs and trees of the target species (Filibeck 2013, Allesi et al. 2018).

Low formations of Euphorbia close to cliffs (5320) dominated by *Helichrysum* and *Euphorbia* spp. are found near cliffs, serving as a transition between cliff vegetation or thorny cushion scrub closer to the sea and thermo-Mediterranean scrub. **Thermo-Mediterranean and pre-desert scrub (5330)** is characteristic of the thermo-Mediterranean zone and Macaronesia, representing succulent scrubland featuring endemic *Euphorbias*, semi-arid thymes, and native *Plumbaginaceae* and *Chenopodiaceae* (Cabello et al. 2009). **West Mediterranean clifftop phryganas – *Astragalo-Plantaginetum subulatae* (5410)** occupy the upper parts of cliffs and are subjected to salt-laden sea winds, restricted to the Costa Brava and reported also from Malta. ***Sarcopoterium spinosum* Phryganas (5420)** is primarily found in the Aegean islands, coastal regions of the southern Balkans, and parts of Sicily and Malta, where it occurs on dry, rocky, and overgrazed calcareous soils. Lastly, **Endemic phryganas of the *Euphorbio-Verbascion* (5430)** thrive on cliffs exposed to salt-laden winds, sharing ecological niches with coastal heath habitats. Their ecological niche is similar to the thickets found in habitat types 4040 and 5410.

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

These habitats show complex responses to environmental controls and natural or human-induced disturbances. Four essential aspects determine their structure and dynamics: soil properties, bioclimatic conditions, topographic and microclimatic characteristics, and successional dynamics. These factors define their spatial distribution, species composition, adaptive capacity, and resilience to global change.

1.2.1 Ecological characterization of heaths and scrubs

Soil properties

Underlying lithology affects soil formation, nutrient and water availability, influencing plant growth and community composition and serving as an environmental control on the dynamics of primary productivity (Cabello et al. 2012a). Heaths and shrublands typically thrive on nutrient-poor or limiting soils, directly influencing the types and diversity of plant species they support. Factors such as soil structure and texture, which affect water retention and aeration, or levels of acidity or alkalinity, limit or favour the growth of particular plants, shaping distinct plant communities.

The chemical composition of the soil determines the availability of essential plant nutrients, although patterns relating soil fertility to plant diversity may vary between vegetation types. Soils derived from acidic rocks maintain the oligotrophic conditions necessary for heathland (Pontevedra-Pombal et al., 2022). However, high organic matter content modifies these properties, favouring fertility and moisture retention, and increased atmospheric nitrogen deposition affects heathland by increasing the cover of herbaceous species (Fagúndez, 2012). Plant species diversity tends to increase as soil fertility decreases, particularly in nutrient-poor or highly weathered soils. This pattern is observed in various shrubland and heathland ecosystems, where reduced resource availability limits the dominance of competitive species and promotes coexistence through niche differentiation (Arroyo & Marañón 1990; Jeffrey 2003; Zemunik et al. 2016).

Beyond general patterns, plant adaptations to specific local soil conditions have driven speciation processes, contributing to increased biodiversity in shrublands. This is the case for gypsum soils, characterised by high sulphate concentrations (Mota et al. 2011, Escudero et al. 2015) and low nitrogen and phosphorus availability (Cera et al., 2023), serpentine soils, with high Mg and low Ca content (Adamidis et al., 2014) and dolomite soils with high levels of magnesium (Mota et al. 2021). Both soil types harbour unique plant communities characterised by plants with specific adaptations to chemical constraints. In addition to the variability in habitat composition, structure and functioning imposed by such adaptations, plant responses to soil biota vary according to nutrient-acquisition strategies, with positive feedback for ectomycorrhizal plants and negative feedback for nitrogen-fixing and non-mycorrhizal plants (Teste et al., 2017).

Bioclimatic conditions

Bioclimatic conditions are crucial in determining the characteristics of Heaths and Scrubs, as temperature and precipitation regimes heavily influence their distribution and ecological adaptations. Heathlands, for instance, vary between the Atlantic (Loidi et al., 2010) and dry Mediterranean climates (Ojeda et al., 1995). In areas of high precipitation, wet heathlands develop on acidic, moist soils, supporting wet-adapted species like *Calluna vulgaris* and *Erica* spp., along with a rich layer of mosses and lichens that reflect the high moisture availability

(De Graaf et al., 2009; Fagúndez & Pontevedra-Pombal, 2022). In contrast, dry heathlands arise in regions with low precipitation and well-drained soils, where drought-resistant species such as *Erica cinerea* and xerophytic vegetation dominate. Mediterranean shrublands display specific adaptations to semi-arid climates with marked seasonal variability. Semi-arid shrublands host drought-tolerant species such as *Anthyllis cytisoides* and *Genista retamoides*. At the same time, the maquis and garrigue communities in slightly wetter areas host species such as *Pistacia lentiscus* and *Quercus coccifera*. These shrublands often exhibit sclerophyllous traits, succulence, and fire-resilience adaptations, including resprouting and fire-stimulated seed germination, enabling survival under arid and fire-prone conditions (Cowling et al., 1996; Keith & Loidi, 2022). Altitude and latitude further shape heath and scrub communities, with higher altitudes in Mediterranean mountains, where low temperatures and high winds impose additional stress on dwarf shrubs in alpine heathlands (Maren et al., 2009; De Toma et al., 2022). Higher elevations often harbour unique endemic species and biogeographical disjunctions, as observed in Southern Spain, where the proportion of Iberian and Ibero-North African species increases (Arroyo & Marañón, 1990). Similarly, on high-elevation islands like La Palma in the Canary Islands, summit regions are hotspots of endemicity (Irl, 2016).

Microhabitat conditions and spatial heterogeneity

Topography influences soil characteristics, humidity patterns, and sunlight exposure, creating distinct microhabitats that support different communities. Vegetation heterogeneity in arid regions arises from processes such as redistribution of water and salt content in the soil, associated with topography (Peñuelas et al., 1999). Microclimatic gradients, mainly associated with soil moisture availability, further determine the spatial distribution of vegetation traits, such as life span, dense foliage, plant recruitment, or seed dispersal syndromes. For instance, fractures in the terrain can determine the local persistence of long-lived shrubs that can tap the groundwater in arid climates, such as *Ziziphus lotus* (Guirado et al. 2018). Dense foliage areas tend to collect more seeds, resulting in higher plant density, while open interspaces may influence recruitment by offering different microsites (Alcántara et al., 2000).

Successional dynamics

Heath and scrub communities can function as early successional stages or climax communities. Under favourable conditions, these shrub formations can gradually develop into forested areas, but human interventions, such as controlled burning or grazing, are essential for maintaining these open habitats by preventing forest encroachment (Rosa-García, 2013; Velle et al., 2023). However, forest succession is not inevitable, as heath and scrub dynamics are often determined by a complex interplay among historical land use, local disturbances, and spatial scales (Terradas, 2001). Under specific ecological constraints that limit the establishment of taller vegetation, heaths and shrubs can represent climax communities. For instance, in Mediterranean mountains, these habitats persist in areas where seasonal rainfall, high evapotranspiration, and prolonged summer droughts prevent forest development. Edaphic limitations, such as nutrient-poor soils, shallow rocky substrates, and fluctuating groundwater tables, further favour shrub dominance. Additionally, high-altitude environments with harsh climatic conditions and xeric south-facing slopes provide settings where shrubs, such as *Juniperus communis* or *Arctostaphylos uva-ursi*, form stable communities. These factors collectively contribute to the dominance of heaths and scrubs as long-term, self-sustaining ecosystems in environments where water availability, soil properties, and disturbance regimes prevent forest succession.

Frequent disturbances, including fire and grazing, shape these landscapes by promoting fire-adapted and resprouting shrub species such as *Erica, Cistus, and Genista*. Fire acts as a central driver in heathland ecology, not only promoting early successional and regressive stages but also allowing species to regenerate in periodic cycles rather than in a unidirectional progression (Harris et al., 2011; Fagúndez, 2012). Heathland plants have vegetative traits, such as thick bark and fire-dependent seed germination, that allow them to withstand periodic fires (Måren and Vandvik, 2009; Keith & Loidi, 2022). High seed production and persistence of seed banks enable these communities to regenerate effectively after disturbances. Other factors modulating succession are dispersal mechanisms such as wind or ants, which facilitate non-linear recolonisation patterns, often maintaining the habitat in a loop between plant establishment and dispersal phases (Rodríguez-Pérez & Traveset, 2009). Indeed, Mediterranean shrubs exhibit multiple demographic strategies, shifting from seedling regeneration to persistence through longevity and vegetative reproduction along gradients of abiotic stress or competition (García & Zamora, 2003).

In arid or mountainous regions, vegetation dynamics are strongly influenced by local environmental constraints, reinforcing the idea that community changes are not necessarily directional but can oscillate within ecological cycles. These non-linear dynamics are also evident in European heathland landscapes, which have been shaped over millennia by cycles of burning and grazing (Evans et al., 2006; Fagúndez, 2012). Local factors, such as habitat fragmentation and historical cultivation, further underscore the role of contingency in shaping shrubland structure (De Toma et al., 2022; Maestre and Cortina, 2005). Areas with a history of cultivation tend to experience slower shrubland encroachment, indicating how land-use legacies create unique successional trajectories within each region (Kepfer-Rojas et al., 2014; Requena-Mullor et al., 2018a).

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

The description of key characteristics and the corresponding variables that are useful to measure scrub condition in this section follows the approach to assess ecosystem condition defined in the framework of the System of Environmental Economic Accounting - Ecosystem Accounting (SEEA EA), adopted by the United Nations Statistical Commission as international standard for ecosystem accounts (United Nations, 2021), which is also integrated and proposed in the EU broad methodology to map and assess ecosystem condition (Vallecillo et al., 2022). According to this framework, ecosystem condition is the quality of an ecosystem, measured by its abiotic and biotic characteristics. The selection of condition variables in the UN System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA) suggests a strong relationship with ecosystem quality or condition: higher values indicate better condition, or, conversely, lower values indicate worse condition (Czúcz et al., 2021).

Abiotic characteristics

Abiotic factors are the physical and chemical components of the environment that affect living organisms and ecosystem processes (Table 1). Some abiotic variables, such as climatic and physical factors, are essential drivers of ecological processes, although they are not always helpful as condition variables (Czúcz et al. 2021). They are included and described below because their monitoring can be beneficial, for instance, in interpreting changes in habitat condition and defining ranges for some variables.

Physical state characteristics

Temperature - precipitation: Temperature, humidity, rainfall patterns, and wind are critical abiotic factors that determine the types of shrubs that can develop. These climatic factors are regional contextual factors that influence the rate of nutrient cycling and decomposition of organic matter, affecting the chemical composition of soils.

Radiation: Solar radiation levels affect soil temperature and moisture, influencing plant growth and survival. The variation in this abiotic factor is essential for understanding ecological processes, such as photosynthesis and primary productivity. Photosynthetic Active Radiation (PAR) is a contextual variable that varies at large spatial scales as a function of latitude, altitude, cloud cover and seasons. However, other factors, such as vegetation cover, orientation, and shade, which operate at smaller spatial scales, also contribute to variation. More radiation favours some species compared to areas with less sunlight. For example, *Calluna vulgaris* thrives in Europe's cool, moist and sunny Atlantic regions. In contrast, with high summer radiation, Mediterranean heaths have plants adapted to drought and high temperatures. Mediterranean shrublands experience solar radiation year-round, which shapes their dynamics and drives foliar adaptations to minimize water loss and protect the photochemical apparatus from damage. In semi-arid ecosystems, photodegradation (the direct decomposition of organic matter by solar irradiation) during dry periods can influence subsequent decomposition in wet periods, with effects varying between deciduous and evergreen shrubs (Gaxiola & Armesto, 2015). At the local level, some shrubs provide shade, allowing less radiation-tolerant species to grow—an example of positive species interactions and resource availability.

Soil physical characteristics: Soil texture, structure, porosity, bulk density, and drainage capacity directly influence the availability of water and nutrients to plants. Soil structure stability is crucial for erosion resistance, a factor that can reduce vegetation cover and compromise habitat regeneration in heathland areas (Ballantyne and Pickering, 2015). Soil compaction decreases infiltration and soil aeration, restricting root growth and limiting the establishment of new species. Heathlands typically have well-drained soils, and changes in soil structure can adversely affect native species. Thus, assessing soil compaction helps to identify areas affected by human activities, such as pedestrian or vehicular traffic.

Soil temperature: Temperature influences decomposition processes and nutrient availability. Monitoring soil temperature can provide information on the microclimatic conditions affecting plant regeneration and growth, as well as the performance of functions such as soil respiration.

Water availability: Monitoring soil moisture levels can be valuable for assessing the suitability of conditions for both heathland and shrubland species, especially during extreme weather events like prolonged droughts or heavy rainfall. Most shrubs in Heaths and Scrubs are adapted to manage both excess and water scarcity, using root and leaf adaptations to maximise water efficiency. Despite specific adaptations to address drought, reduced rainfall, or groundwater levels due to climate change (or over-extraction) pose a serious risk to these ecosystems, potentially impairing their functionality and resilience.

Chemical state characteristics

Soil pH and fertility properties: The critical chemical properties for assessing shrubland habitat condition include pH, nutrient levels (nitrogen, phosphorus, potassium) and heavy metal concentrations. Monitoring these properties is crucial for providing information on the effects of specific biotic or stress factors on the community. For example, flowering phenology and pollinator interactions of *Calluna vulgaris* are modulated by the nutrient cycling activity of mycorrhizal fungi (de la Peña et al., 2012), cattle density correlates positively with soil nutrient levels (Fagúndez & Pontevedra-Pombal, 2022), and the excessive nitrogen from deposition can disrupt native species by encouraging invasive species growth.

Soil organic matter content: Soil organic carbon (SOC) is a crucial indicator of soil quality and ecosystem function in Mediterranean regions facing desertification risks, as well as of carbon sequestration capacity. SOC quality varies with parent material, climate, and vegetation type, with calcareous and calcareous/volcanic soils showing higher biogeochemical transformation than acid metamorphic soils (Aranda & Comino, 2014). High organic matter content indicates soil fertility and ability to retain moisture, with fluctuations potentially signalling shifts in ecosystem dynamics. Shrubs that produce large amounts of leaf litter in arid areas enhance soil biological activity, thereby contributing to soil fertility (Torres-García et al., 2022). Studies have shown that SOC content below 20 g/kg can rapidly deteriorate soil properties, emphasising the need for effective management strategies (Grilli et al., 2021).

Biotic characteristics

Compositional state characteristics

These characteristics refer to the variety and abundance of species inhabiting these habitats, including dominant plants and associated species (Table 1). This category comprises several groups of characteristics.

Characteristic species: are those typically found in a particular habitat type whose presence, abundance, or behaviour reflects specific ecological conditions of the environment. These species play a significant role in ecosystem structure, functionality, and stability, and serve as indicators of habitat condition. There are several types of characteristic species: 1) Do**minant species**, those with the greatest biomass or coverage, shape community structure and composition, such as *Calluna vulgaris* in heathlands or *Juniperus communis* in some scrublands. 2) **Indicator species** reflect specific habitat conditions, like pH, moisture, or nutrient availability, and their presence or absence can signal habitat quality or disturbance levels. 3) **Ecosystem engineer species** modify, create or maintain the physical environment in which they live, significantly influencing the availability of resources and the structure of ecosystems. These modifications, directly or indirectly, affect other species, thereby altering biodiversity, ecosystem dynamics, and ecosystem services. Such is the case of shrubs that create mesic patches that facilitate forbs and scrubs (Tirado, 2009; Constantinou et al., 2021, 2023), soil biota, and even animal communities (Rey et al., 2018) in Drylands. 4) **Endemic species** are confined to specific combinations of environmental and phenotypic conditions, which explains their limited distribution. These restrictions often result from their evolutionary history in particular habitats. The strong integration between phenotypic traits and environmental factors can drive specialization in these habitats, making endemic species especially vulnerable to environmental changes, including those caused by climate change (Hermant et al. 2013). Such species are particularly significant in Mediterranean shrublands associated with calcareous, gypsum, serpentine, and dolomite soils or under specific bioclimatic and biogeographical conditions. Due to their high dependence on local environmental conditions, endemic species serve as valuable indicators of habitat quality. They reflect the response of rare species to disturbances and habitat degradation (Lavergne et al., 2004; Mendoza-Fernández et al., 2015b; Buira et al., 2020).

Species richness: Monitoring species richness provides crucial insights into habitat health by indicating biodiversity levels, ecosystem functionality, and habitat quality. High species richness is associated with resilient habitats, while low richness may indicate degradation.

Understanding species richness protect species of conservation concern and maintain ecosystem function. Their decline or loss can have cascading effects on other species and ecosystem processes.

Invasive non-native species: Biological invasions vary among habitats and biogeographical regions, with factors such as insularity, low elevation, and resource availability promoting invasions (Künzi et al., 2015; Kalusová et al., 2023). Disturbances such as land-use changes, pollution, and climate change can create opportunities for invasive species to establish and spread (Affre et al., 2010). Heathlands are highly vulnerable to biological invasion (Fagundez, 2012), but Mediterranean scrublands are relatively resistant to invasion by non-native plant species compared to other habitats in the region (Affre et al., 2010; Gaertner et al., 2009). The impact of invasive non-native species on native ones can be substantial at more minor spatial scales and when measured over extended periods, whilst certain growth forms can give such species a strong competitive advantage (Gaertner et al., 2009). Examples of invasive non-native species frequently found in heaths and scrubs are *Agave sisalana, Agave fourcroydes, Acacia spp., Amorpha fruticosa, Carpobrotus edulis, Cortaderia selloana, Pennisetum setaceum, Prunus serotina and Lantana camara*. *Rhododendron ponticum* forms dense thickets on wet heaths that outcompete native vegetation.

Harmful species: Some native species can also negatively impact habitat condition by dominating composition, structure, or function, often due to their high colonization ability or growth rate. These species, sometimes called "expansive," frequently appear after disturbances or increased nitrogen deposition and can act as indicators of habitat alteration. Examples of such species are: 1) *Pteridium aquilinum*, which can increase in open heathlands significantly when fire or the cessation of traditional management reduces competition; *Ulex europaeus* that become dominant in degraded heathlands and scrublands with recurrent disturbances like fire or heavy grazing, limiting resources and space for other plants; *Cistus ladanifer* that can spread rapidly in acidic, nutrient-poor soils after fires in Mediterranean scrublands, outcompeting less fire-tolerant native species and reducing habitat diversity; and *Rhododendron ponticum* that forms dense thickets that outcompete native vegetation, while bracken and trees like birch and pine indicate habitat decline when they encroach into heathlands.

Structural state characteristics

Structural complexity in the vertical profile can enhance biodiversity. Variations in shrub height, density, and microhabitat presence contribute to robust heathland and scrubland ecosystems (Table 1). Diverse microhabitats, such as open areas, dense shrub patches, and transitional zones, support different species and ecological processes, contributing to landscape heterogeneity and stability.

Vertical structure: refers to layering plant life within an ecosystem, from ground level to canopy. In shrublands, measuring vertical structure is crucial for understanding habitat complexity and its effects on wildlife. Metrics such as vegetation height and visual obstruction provide insights into cover, nesting sites, and microclimatic conditions (Harrell & Fuhlendorf, 2002). These measures are also highly correlated with other dimensions of habitat variability, making them key for evaluating responses to land management practices. Height inequalities, linked to size-asymmetric competition and niche complementarity, help explain diversity-productivity relationships and provide insights into ecological assembly mechanisms (Brown & Cahill, 2019). Vertical structure typically includes strata like ground cover, shrub layer, understory, and canopy, each offering unique habitats and resources. This arrangement influences light availability, microclimate, and species interactions, driving ecosystem complexity, biodiversity, and function. Vertical structure also reflects habitat dynamics. For example, homogeneous shrub heights often indicate regular disturbances like grazing or burning, which limit overgrowth. Tools such as LiDAR and spectral data effectively estimate shrub biomass and height, providing valuable resources for assessing and managing these ecosystems.

Horizontal structure (coverage): The horizontal structure of shrublands includes a mixture of habitats, such as open areas, dense thickets, and transition zones, whose spatial distribution determines the distribution of microhabitats that influence species diversity and ecosystem dynamics. Because of this, ground and vegetation cover (Hamada et al., 2010), including biocrusts (Briggs & Morgan, 2008), are recommended variables for monitoring shrubland communities. High shrub density with more than 70% cover suggests a healthy ecosystem with sufficient regeneration. Dense foliage areas tend to collect more seeds, resulting in higher plant density, while open interspaces may influence recruitment by providing different microsites (Alcántara et al., 2000). In heathlands with high vegetation cover, the predominance of low, semi-sclerophyllous shrubs such as *Calluna* and *Erica*, interspersed with grasses and ferns, indicates a good condition. In Atlantic wet heathlands, optimal habitat quality is characterised by a heterogeneous vegetation structure with shrubs around 0.5 m tall and consistent gaps (Muñoz-Barcia et al., 2019). From a successional perspective, the ratio of shrub to herbaceous cover may indicate whether the habitat is in an early (higher herbaceous cover) or advanced (higher shrub cover) stage. Mosses and lichens in the lower layers indicate low levels of disturbance, as biological crusts play a crucial role in soil properties, especially in arid areas (Condon & Pyke, 2020).

Functional state characteristics

Functional characteristics determine how the biota responds to environmental controls and disturbances and the ability of ecosystems to provide ecosystem services. This category comprises several groups of characteristics (Table 1):

Key processes such as **primary productivity, nutrient cycling, and organic matter decomposition** directly influence ecosystem health and resilience (Maes et al., 2023). Aboveground net primary productivity (ANPP) is a highly integrative indicator for monitoring shrubland health, reflecting ecosystem responses to water availability, nitrogen dynamics, and vegetation changes (McNaughton et al., 1989; Peñuelas et al., 2007). ANPP is particularly sensitive to climatic variability, including drought, warming, and extreme events, which can reduce productivity and alter biodiversity and ecosystem structure. In arid and semi-arid environments, water availability, driven by soil moisture and precipitation, is the primary control on ANPP (Epstein et al., 2012). Short-term rainfall events create nitrogen pulses that temporarily boost productivity, while long-term precipitation patterns shape soil moisture and nutrient dynamics. Monitoring ANPP also provides insights into ecohydrological factors, such as root depth, rainfall-use efficiency, and precipitation thresholds (Parolari et al., 2015). In desertified areas, ANPP reflects shifts in vegetation composition and ecosystem functionality, serving as a critical measure of land degradation and restoration success (Huenneke et al., 2002). Spectral indices, such as NDVI, enable efficient monitoring of ANPP (Alcaraz-Segura et al., 2009; Cabello et al., 2012b).

Functional traits of plant communities: such as growth form, root depth, resource use efficiency, and symbiotic relationships, also highlight adaptations to environmental conditions and their roles in nutrient cycling, carbon sequestration, and resilience (Lawson & Keeley, 2019). The decomposition of organic matter is a valuable indicator for monitoring shrubland ecosystems, as it reflects key soil functions, including nutrient cycling, carbon sequestration, and soil fertility. Mixed thickets have a greater diversity of plant residues with different chemical and physical characteristics. This creates a more favourable habitat for microbial communities and soil fauna, thereby increasing decomposition intensity (Kooch & Dolat Zarei, 2023). These results highlight how vegetation composition influences decomposition rates and soil health, making organic matter decomposition an effective tool for assessing and managing shrubland ecosystems. Methods such as soil CO_2 flux analysis, spectral time-series data, and metabolomics provide valuable insights into ecosystem function.

Ecosystem phenology: the study of periodic biological events and their relationships with environmental changes, is a crucial tool for understanding the dynamics of shrubland ecosystems. Shrublands are sensitive to climate variability. Phenological events, such as leaf emergence, flowering, and senescence, are highly responsive to temperature, precipitation, and other climatic factors. Shifts in phenological events can cascade into changes in species interactions, including herbivory, pollination, and seed dispersal. Changes in ecosystem phenology are valuable indicators of ecosystem health and condition, as they reveal responses to environmental stresses and successional stages. NDVI dynamics provide a measurable means to detect changes in ecosystem phenology, helping assess how climate-driven changes can alter ecosystem functioning (Alcaraz-Segura et al., 2009; Cabello et al., 2012b).

Biotic interactions: Monitoring biotic interactions, such as pollination, seed dispersal, plant-plant facilitation, and phytophagy—including dynamics of species like *Lochmaea suturalis* in *Calluna* heathlands (Gillingham et al. 2015)—is essential for assessing the conservation status of heathlands and shrublands. These habitats host a diverse array of pollinators (including flies, butterflies, bees), birds, and even some mammals, which are critical for plant reproduction and ecosystem resilience (Forup et al., 2007; Rey et al., 2018; Ropars et al., 2020). A robust pollinator community enhances plant diversity through effective cross-pollination and seed production, fostering an adaptable ecosystem resilient to environmental shifts. Seed dispersal, primarily by birds, mammals, and reptiles, further supports population maintenance. Plant-plant facilitation occurs when larger “nurse” shrubs create microhabitats by providing shade, retaining soil moisture, and reducing temperature extremes, which helps smaller or more sensitive plants survive in harsh conditions (Danet et al., 2024). This sheltering effect allows a variety of species to establish and grow under challenging environmental conditions, enhancing overall ecosystem stability. Under mesic conditions, competitive relationships tend to dominate over facilitative ones, leading to spatial segregation among species. Climatic conditions influence the nature of these biotic interactions, especially plant-plant facilitation. Keystone species, such as nitrogen-fixing plants in *Juniperus communis* shrublands, play disproportionate roles in maintaining ecosystem structure and enhancing biodiversity, notably influencing bird assemblages (Fartmann et al., 2022).

Successional stages: They refer to the continuity of the different successional stages, that is, to the ability to appear, to regenerate or remain after disturbance, or to transform the habitat type into another one. Sclerophyllous scrubs and heaths develop in the early and middle stages of succession, stabilising the soil, accumulating nutrients and modifying microclimates to create favourable habitats for other plants, contributing to the development of the ecosystem towards more complex habitats. When environmental and human controls permit, shrublands can transform into forested areas over time. Transitions between stages are also influenced by soil fertility, water availability, and seed availability. Disturbances mainly determine them, each acting differently depending on their frequency and severity.

Transition from habitats 5230 & 5330 to 9330, driven by favorable soil, water, and seed conditions.
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Fire regime: Fire is a natural and essential process in many shrubland ecosystems, with frequency and intensity shaping vegetation structure and composition. Recurring low-intensity fires are critical in heathlands, preventing forest encroachment. Controlled burns (and grazing) create light gaps, promoting seed germination and seedling establishment. These practices maintain structure, composition, and functionality by reducing dominant plant density, allowing less competitive species to thrive, lowering uncontrolled fire risks, enhancing structural diversity through vegetation mosaics, and supporting the regeneration of species that need open spaces.

Landscape characteristics

When studying the functional relationships in landscapes, vegetation is seen as a result of constraints imposed by higher-level environmental factors, such as climatic processes, geomorphology, hydrology, and sediment transport, which serve as the fundamental elements explaining the distribution of communities in the territory. Measuring mosaics at the landscape level involves a combination of spatial, structural, and functional metrics. Spatial patterns of vegetation patches can indicate habitat quality and landscape structure (Viedma & Meliá, 1999). In traditional landscapes, human activities strongly influence mosaic structure.

The variables used to assess landscape characteristics include metrics commonly used in landscape ecology, such as extent, fragmentation, edges, and mosaicity (Table 1). Extent refers to the patch size, area, or coverage within the landscape context. It describes the physical spread or range of a specific land feature or habitat type, highlighting the connectivity and distribution pattern.

Fragmentation can lead to reduced population sizes, loss of habitat connectivity, increased edge effects, and decreased genetic diversity. These effects can make shrublands and heathlands more vulnerable to species loss, exotic species invasions, and reduced resistance to environmental stressors. Assessing the spatial arrangement of patches, including measuring patch size and distances between them, helps identify patterns of clustering or dispersion. Edges can influence species composition, nutrient cycling, and movements, creating unique conditions and species assemblages. "Mosaic" applies to situations in which habitats appear patchy across the territory. It refers to a heterogeneous structure produced by any cause, whether reflecting environmental heterogeneity or resulting from a different history of disturbances (Terradas, 2001).

Table 1. Key ecological characteristics and selection of variables to measure habitat condition

Ecological characteristics	Types	Description of associated variables	Examples of variables
Abiotic characteristics	**Physical state characteristics**	Variables based on climatic factors and physical properties of the soil	- Temperature and precipitation - Humidity - Solar radiation - Soil Structure and Texture - Seasonal and daily fluctuations of soil temperature - Soil water
	Chemical state characteristics	Variables based on soil chemical properties	- Soil pH - Nutrients (N, P, and K) - Organic Matter Content - Elements and Contaminants (e.g. Pb, Cd)
Biotic characteristics	**Compositional characteristics**	Variables based on the evaluation of assemblages of species	- Characteristic species (e.g., dominant, indicator, ecosystem engineer, endemic) - Species Diversity - Invasive species - Harmful species
	Structural characteristics	Variables based on the structure and complexity of the habitat	- Tall shrubs and trees - Vegetation Cover - Biological crust cover (mosses, lichens) - Herbaceous plants cover - Small-scale habitats (e.g., open areas, dense shrub patches).
	Functional state characteristics	Variables based on ecological processes and ecosystem functions	- Primary Productivity - Ecosystem phenology - Soil biological activity - Biotic interactions (Pollinator Activity, Seed dispersers) - Successional stages - Recovery after disturbances - Fire regime (frequency and intensity)
Landscape/ seascape characteristics		Variables based on the spatial patterns of vegetation patches at landscape level	- Patch Size - Habitat Connectivity and Fragmentation - Edge Effects - Mosaic and Spatial Heterogeneity

1.3 Selection of typical species for condition assessment

Although the Directive uses the term ‘typical species’, it does not give a definition that can be used in the assessment and reporting on the conservation status of habitats. Little guidance has been provided on how to use the typical species in this assessment. The term ‘typical species’ is part of the definition of Favourable conservation status for a habitat type given in Article 1(e). For a habitat type to be considered as being at Favourable conservation status, the Directive requires its structure and functions to be favourable and its ‘typical species’ to be at favourable conservation status.

According to the Guidelines for Reporting under Article 17 of the Habitats Directive (European Commission, 2023), the assessment of typical species is included as part of the assessment of structure and function parameters.

The formulation of Art. 1(e) might suggest that the assessment of typical species could be carried out separately and complemented in the evaluation of structure and function. In this regard, the selection of typical species should be as robust and appropriate as possible. According to the analysis of national methodologies available for assessing habitat structure and function, some MS assess the typical species separately and then integrate both assessments into the overall result to determine habitat condition, while others include the typical species in the evaluation of compositional characteristics.

All MS have communicated a list of typical species for each habitat type[1], although they usually have not provided any justification or rationale for their selection. The variability in MSs' selection of typical species indicates that different approaches and interpretations are used. Mostly plants are proposed as typical species (> 90% of the selected species), and in many cases, dominant or characteristic species are included. However, species from other taxonomic groups are also considered (e.g., lichens, insects, birds, mammals…).

It has long been clear from the MS reports that they interpreted the typical species differently, meaning the lists produced have probably had limited value. Therefore, the consideration of "typical species" in the assessment of the habitats' conservation status still needs to be discussed and clarified.

Recommendations for the selection of typical species

According to the guidelines for reporting under Article 17, the selection of 'typical species' for Article 17 reporting should reflect favourable structure and functions of the habitat type. When choosing typical species for reporting under Article 17, the following considerations should be considered (European Commission, 2023):

- 'Typical species' selected for Article 17 reporting should include species that **are good indicators of favourable habitat quality and species sensitive to changes in the condition of the habitat** (e.g. 'early warning indicator species').
- Typical species **may be drawn from any species group**. While vascular plants are commonly selected, lichens, mosses, fungi, and animals (particularly invertebrates) also play critical roles in ecosystem function (e.g., pollination, litter decomposition) and should not be overlooked (Table 2).
- The **dominant species may not be a good choice** for monitoring typical species, as they are usually assessed as part of the habitat composition; therefore, they are not always ideal as typical species.
- Given the **ecological and geographical variability of the Annex I habitat types**, it is not realistic to have recommended fixed lists of typical species, even for a biogeographical or marine region. Indeed, even within a single Member State, **different species may be present in various parts of the range of a habitat type or in other subtypes**.
- Given the variability of habitat types across their range, even within a single biogeographical or marine region, **it is improbable that all typical species will be present in all examples of a given habitat type**, particularly in large Member States.

[1] The compilation (for all habitat types and MS) is available at: https://cdr.eionet.europa.eu/help/habitatsart17

However, the sum of sites and occurrences of each habitat type should, on a long-term basis, **support viable populations** of the typical species within the region being assessed, for Structure and functions to be favourable.

- **Many species may be typical for several habitats** (including non-Annex I habitats) and not dependent on a single Annex I habitat type. Such species may be threatened (e.g. red-listed) at a national or regional scale even though they thrive in the habitat and region being assessed.

The concept of 'typical' species used for habitat assessment (EC, 2023) differs significantly from that used in the phytosociological school, as it is not strictly focused on the species' diagnostic value. According to the mass ratio hypothesis (Grime 1998), ecosystem functioning is mainly determined by the most abundant species (and their features); therefore, the overlap between “diagnostic”, “characteristic” and “typical” species is driven by their abundance (Bonari et al. 2021). Gigante et al. (2016) suggest that in species-poor habitats or in habitats clearly defined by the dominance of a restricted group of species, diagnostic species (physiognomy-shaping) may serve as typical species. However, in species-rich habitats, the entire floristic pool should be considered the best proxy for assessing conservation status. Some indicator species can serve as indicators of ecological conditions, including bioclimatic and soil conditions.

Like plants, certain animals can adapt to specific conditions and play significant roles in the ecosystem structure and function. A wide range of animal species can be used as typical species for shrubland assessment. Some mammals (e.g., rabbits, foxes, badgers, hedgehogs) respond negatively to increased vegetation structural complexity resulting from land abandonment and post-fire recovery (Torre Corominas, 2004). Open scrublands support diverse bird communities (e.g., blackbirds, small passerines, nightjars, larks) in natural and seminatural landscapes, with different species preferring different habitat types (Covas & Blondel 2008, Montesinos & García 2009, Šálek et al. 2022). The endangered Dupont's lark (*Chersophilus duponti*) selects flat, deforested areas with small shrubs, including supramediterranean dwarf cushion scrubs, *gypsicolous* shrublands, *chamaephyte*-dominated shrubs, and acidophilous scrubs (Aguirre et al., 2018). Amphibian (toads and frogs) and reptilian (lizards and snakes) species, which are at risk of extinction and have restricted distribution ranges, have also been used to propose an index for scrublands whose conservation is of the highest priority (Egea-Serrano et al. 2006). Finally, several studies suggest that insects such as *Hemiptera, Isoptera, Orthoptera, Thysanoptera, Coleoptera, Diptera, Hymenoptera*, and *Lepidoptera* are major insect orders commonly recognized and studied across various environments. In arid and xeric shrublands of the Iberian Peninsula, insect diversity is particularly high, likely due to the rich diversity of bee-pollinated plants characteristic of these environments (Piñeiro et al. 2011). Ground-dwelling arthropods show distinct preferences between shrubland and grassland, with opilionids and some carabids preferring shrubland (García et al., 2011).

Keystone and ecosystem engineer species could be valuable for selecting typical species. **Keystone species** exert a disproportionately large influence on ecosystem structure and processes relative to their small abundance (Power et al. 1996). By focusing on keystone species, we can gain insights into the overall health and functioning of the ecosystems. These species often regulate population interactions, shape community composition, or enhance habitat quality. A compelling example is *Launaea cervicornis*, an endemic cushion-forming plant of coastal Balearic shrublands. Despite its limited distribution, it plays a critical role in maintaining ecosystem integrity. Its abundant flowering and fruiting support diverse pollinator communities, facilitate the progressive colonization of other plant species, and profoundly influence the soil environment. The removal of *L. cervicornis* can trigger cascading effects that alter both the structure and functioning of the shrubland. For these reasons, it is recognized as a keystone species in this coastal habitat (5320) (Llorens et al. 2009). **Ecosystem engineers** exert a substantial influence on the physical structure of ecosystems, altering resource availability and shaping biodiversity patterns. An example of an ecosystem engineer species in shrubland habitats is the European Rabbit (*Oryctolagus cuniculus*), whose burrowing and grazing activities create favourable habitats for themselves and other species (Beja et al., 2007; Kämpfer & Fartmann, 2019).

In conclusion, typical species may be drawn from any species group. Heaths and scrubs simultaneously provide animals with food, shelter, reproductive opportunities and protection from predators. Thus, there is a wide range of animal species in these habitats that could serve as typical species for their conservation assessment.

Table 2. Illustrative list of species groups that can be used to select typical species

Species Group	Ecological role	Sensitivity to	Indicators of
Ants	Soil aeration, nutrient cycling, and seed dispersal. Also act as predators and ecosystem engineers. Some form mutualisms with Lycaenid butterflies. e.g.: *Messor barbarus*, key seed harvester in Mediterranean scrublands.	Disturbance, vegetation change, and pesticides; community shifts reflect microhabitat structure and land use.	Changes in ant communities reveal habitat condition and soil quality. Mutualisms with butterflies indicate functional integrity, while opportunistic dominance suggests ecological stress.
Amphibians	Insect population control and nutrient cycling. e.g.: *Bufo bufo* (Common Toad), widely distributed in European scrublands.	Moisture, pollution, and microclimate; vulnerable to fragmentation and climate change.	Population declines indicate habitat degradation from hydrological or chemical stress. Amphibians are early warning indicators and priority species for assessment.
Bees	Key pollinators of heathland flora, supporting plant reproduction, floral diversity, and food webs. e.g.: *Andrena, Halictus, Bombus* spp. in dry open habitats.	Floral loss, pesticides, fragmentation, climate stress, and soil disturbance.	Bee declines signal floral loss, fragmentation, or pesticide impact; specialists indicate diverse, stable habitats and pollination function.
Beetles	Nutrient cycling, decomposition, and pest control. e.g., *Pimelia* sp. (Tenebrionidae), a detritivore in arid scrublands.	Soil disturbance, vegetation loss, and microclimatic changes that affect shelter, food, and activity.	Reflect key ecosystem processes such as detritus cycling and microhabitat stability.
Birds	Diverse functions: insectivory, seed dispersal, pollination, habitat modification, and prey for predators. e.g.: *Lullula arborea, Chersophilus duponti* in open scrublands.	Vegetation structure, fragmentation, and disturbance require microhabitat heterogeneity for nesting and feeding.	Bird community shifts indicate habitat quality and connectivity; specialists signal high value, declines reflect degradation. Birds serve as umbrella indicators.

Species Group	Ecological role	Sensitivity to	Indicators of
Butterflies	Key pollinators in heaths and scrublands are also vital prey for insectivores. e.g.: Polyommatus *bellargus* (Adonis Blue), linked to dry, flower-rich scrub.	Floral loss, fragmentation, pesticides, and climate shifts; many have narrow niches and low dispersal capacity.	Butterfly trends indicate shrubland quality and connectivity; declines signal intensification, climate change or habitat degradation.
Bryophytes	Aid in moisture retention, erosion control, and microhabitat formation. e.g.: *Sphagnum* (humid heaths), *Didymodon, Tortula* (dry scrubs).	Pollution, humidity, light, and soil compaction; many are microhabitat specialists.	Bryophyte shifts reflect microclimate, soil health, and moisture; declines signal degradation, and richness indicates stability.
Fungi	Nutrient cycling, decomposition, and mycorrhizal symbiosis (e.g., *Cistus, Erica, Quercus*). e.g.: *Russula, Laccaria* spp.	Soil properties, disturbance, pollution, and microclimate are affected by habitat simplification and host plant loss.	Fungal diversity reflects soil health and ecosystem maturity; declines or opportunist dominance suggest degradation or early succession.
Lichens	Nutrient cycling, soil formation, and moisture retention offer microhabitats for invertebrates. e.g.: *Cladonia* spp.	Pollution, light, microclimate, and substrate; some indicate continuity, others early succession.	Lichen diversity reflects air quality and habitat continuity; richness signals stability, and the dominance of tolerant species suggests degradation.
Mammals	Act as carnivores, herbivores, seed dispersers, and ecosystem engineers through grazing and burrowing. e.g.: *Lepus europaeus, Oryctolagus cuniculus*.	Habitat structure, shelter, and land use; specialists decline with homogenization, generalists may increase.	Mammal trends reflect habitat quality and complexity; ecosystem engineers signal functional integrity, and their loss indicates ecological disruption.
Moths	Pollinate night-blooming plants, serve as prey, and aid in nutrient cycling. e.g.: Hyles euphorbiae in dry scrub with *Euphorbia* spp., *Buccolatrix ziziphella* in 5220.	Sensitive to host loss, light and pesticide exposure, and vegetation change; specialized diets increase vulnerability.	Larval outbreaks may indicate imbalance and vegetation stress. Monitoring should assess both diversity and abundance.
Reptiles	Predators of invertebrates, helping regulate prey; some (Podarcis spp.) act as incidental pollinators. e.g., *Lacerta agilis, Podarcis lilfordi*.	Habitat structure, sunlight, microhabitats, and vegetation cover are vulnerable to fragmentation, predators, and climate extremes.	Microhabitat and thermal conditions; specialists indicate intact shrublands, declines suggest degradation. Their pollination role adds value, especially on islands.
Spiders	Generalist predators regulate arthropod populations and support vegetation balance; some create complex webs or refuges. e.g.: *Zodarion, Lycosa, Pardosa* spp.	Vegetation structure, soil cover, microclimate, and disturbance; many show strong microhabitat preferences.	Spider diversity and guild shifts reflect habitat complexity, disturbance, and trophic balance.
Wasps	Diverse groups, including parasitoids, predators, and opportunistic pollinators, also serve as prey in food webs. e.g.: *Cotesia, Neanastatus, Polistes, Vespula* spp.	Habitat structure, host/prey availability, pesticides, floral resources, and climate variation.	Wasp diversity signals ecological balance; declines suggest disrupted food webs or habitat simplification.

How to use typical species in the condition assessment?

The assessment of typical species is part of the assessment of the structure and function parameter; however, a complete assessment of the conservation status (as for species listed in Annexes II, IV, and V) of each typical species is not required (European Commission, 2023).

The assessment of typical species could be conducted separately from the evaluation of the remaining structure and function variables, and both assessments should then be integrated. Evaluation of typical species can be done at the local scale (monitoring plot/station), e.g., by assessing their presence and abundance; however, an overall assessment at a larger scale should also be carried out, e.g., by considering the number of localities with the species present. The evaluation of typical species will require defining thresholds or ranges to determine their condition (e.g., frequency or abundance, area/number of localities) based on species ecology and distribution patterns. It should be noted that, according to the Article 17 guidelines (EC, 2023), the sum of sites and occurrences should support viable populations of the typical species on a long-term basis within the region being assessed, with the structure and functions of the habitat being favourable.

Chrysotoxum festivum, Cevennes, France.

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

Methodologies for assessing and monitoring heaths and scrubs have been collected and screened from 20 EU countries (see Table 3). These methodologies cover all habitat types included in this group, except for 5140 (*Cistus palhinhae* formations on maritime wet heaths), which are only present in Portugal and are not covered by any of the methodologies.

Quite often, standard or very similar methods are developed and applied to assess and monitor all the heath and scrub habitat types present in a country. However, some countries have developed specific methodologies for some groups or subgroups (e.g., 4010, 4020, 4030). Methods developed for sclerophyllous scrub sometimes also cover other scrub habitat types included in the Coastal and halophytic habitats group.

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

The description of variables presented below is based on the analysis of methodologies available and considered in this study (Table 3). The table in Annex provides further details.

Physical variables

At least half of the national methodologies considered in this analysis use physical variables to assess heath and scrub habitats (see Table 3 at the end of this section, and the Annex for more details). Key physical variables assessed include soil and surface characteristics, hydrological conditions, and conductivity. Specific methods range from in-field measurements to remote sensing or lab methods. Threshold values are not indicated for most variables.

Soil physical characteristics indicated in the methodologies include soil compaction level, texture, and depth. Some methods include the percentage of skeletal soils and substrate type (e.g., from Romania, Greece and Cyprus). Erosion levels are measured in Hungary and Greece, presumably during fieldwork via visual assessment, although this is not explicitly stated in the respective methodologies. The surface characteristics and slope degree are measured in Hungary and Romania during fieldwork surveys using a clinometer or derived from Digital Elevation Models. The percentage of bare soil is included in the methodologies of Romania and Ireland, considering its relationship to the species' germination capacity in the habitat.

Some methodologies address hydrological conditions, such as the presence of water or the average groundwater level (e.g., from Poland, Cyprus, Belgium-Flanders, Hungary, and the Netherlands). Shallow-water conductivity is measured in Belgium-Flanders at 25 °C, but no reference values are provided.

Gaps remain in tracking certain critical physical variables. Notably, variables measuring temperature, radiation exposure, and non-contextual variables such as organic matter photodegradation and soil temperature were not detected during the screening of the methodologies. These factors, particularly non-contextual ones, could further clarify the ecological responses of these habitats under varying environmental stresses. This gap highlights areas for potential improvement in monitoring the physical conditions of habitats.

Chemical variables

Chemical variables are included in at least five national methodologies (from Belgium-Flanders, Denmark, the Netherlands, Spain and Romania). The main chemical variables assessed include the soil ammonium/nitrate ratio, air nitrogen deposition, soil nutrient levels (e.g., C/N ratio in Denmark), soil pH, organic matter content, and the nitrogen-to-phosphorus (N/P) ratio. Abiotic favourable ranges and an extensive list of chemical elements and ratios (20 variables) measured in the soil and groundwater in Belgium (Flanders) are provided. Methods used range from in-field water extraction to determine ammonium/nitrate ratios to deposition measurements of air nitrogen and soil sampling for nutrient content and pH levels. Based on the frequency of chemical variables assessed, the most closely monitored habitats are 4030, 4010, and 5130. Gaps remain in monitoring specific habitats and in providing comprehensive metrics for organic matter content and N/P ratios, which are inconsistently recorded.

Compositional variables

All the methodologies considered in this analysis include compositional variables, and most of them provide threshold values and measurement methods. A predominant focus is on characteristic species, particularly dominant and indicator species, which are critical for assessing habitat structure and function. Some national methodologies also include assessing typical species in specific habitats (e.g., heath habitats in Belgium-Flanders; Westra et al. 2022). Vascular plants, ferns, and mosses are considered in Germany. The number of bryophyte or non-crustose lichen species present is assessed in Ireland for habitat type 4030 (Perrin et al. 2014), and the presence of epiphytic lichens is measured in Poland for habitat type 4070 (Mróz, 2010). Species richness and abundance of perennial species (trees, shrubs, and herbaceous) and key, endemic, and exotic species are indicated by the methodologies of Spain and Greece, but neither provides measurement methods or thresholds. The methodologies of Ireland, Poland, Denmark, and Bulgaria indicate the percentage of invasive and other negative species. Species indicative of trophic enrichment are included in the assessment of Atlantic heaths in France (Mistarz & Grivel, 2020). The presence of protected and endemic species is also covered in some methodologies (e.g., from BE-Flanders and Spain).

Common methods include vegetation relevés, transect analyses, and visual inspections, and metrics vary depending on the methodologies, with frequent use of species cover and relative abundance measurements to assess dominance, diversity, and richness indices to evaluate habitat health. Three methodologies include monitoring fauna: Spain, Italy (which refers to entomofauna, avifauna, and mammals, but needs to provide details on the methods used), and the Netherlands (which includes butterflies).

Structural variables

Habitat structural complexity is an emergent property of ecosystems that directly shapes their biodiversity, functioning and resilience to disturbance. The methods used across most Member States consistently focus on vertical and horizontal habitat structure. Vertical structure variables, measured by Poland, Cyprus, Belgium, and France, include shrub (and tree) height. France and Belgium use methodologies to measure woody plant coverage at different heights and tree cover (Mistarz and Grivel, 2020; Westra et al., 2022), while Italy uses dendrometric surveys. These metrics, evaluated through visual assessments, provide insights into habitat maturity and disturbance levels (e.g., afforestation), particularly in habitats such as 4030 and 4060, where layered vegetation supports nesting, shelter, and nutrient cycling.

Regarding horizontal structure, Austria, Poland, Bulgaria, France, Germany, Latvia, Denmark, and Ireland measure the coverage of trees and herbaceous plants, and particularly shrubs, recognising their role in creating microhabitats. Coverage of invasive species and disturbance indicators are also included. Moss or lichen coverage, as indicators of minimal disturbance and good habitat condition, are included as variables in the methodologies available from Austria, Poland, Bulgaria, France, Germany, Latvia, Denmark, Ireland and Belgium. The assessment of horizontal structure is often conducted through field surveys and visual inspections.

Assessment of age structure using expert knowledge is included in the methodologies of Belgium, Germany, and Denmark to capture different vegetation growth stages. Other variables related to age structure include the coverage of *Calluna vulgaris* across different growth phases and its senescent proportion, which are included in Ireland's methodology and provide reference values. The volume of juniper trunks is measured for habitat 5130 in Lithuania. The hypothesis is that a balanced distribution of juvenile, mature, and senescent phases supports regeneration and ecosystem stability. Openings and gaps in vegetation, a variable measured by Poland, Austria, and Slovakia, provide additional information on habitat heterogeneity, supporting diverse species interactions.

Many of the methodologies considered in this analysis include coverage of non-native, invasive, and harmful indicator species (e.g., *Pteridium aquilinum*, ruderal, and nitrophilous species) (e.g., from Belgium, Germany, Ireland, Hungary, Lithuania, and Poland).

Functional variables

Functional variables have received less attention and primarily focus on assessing regeneration or recruitment, successional stages, and disturbance indicators. Variables related to regeneration usually measure the presence and abundance of seedlings (e.g., Belgium-Flanders, Ireland, Lithuania) or Visual expert assessment of shrub regeneration (e.g., Poland). Recruitment is included in the methodology available from Spain, where it is measured through a semi-quantitative estimation of density at the plot level, mainly for key species, considering plants older than one year with no signs of lignification and lignified recruited individuals that have not fully reached the reproductive stage. However, no threshold values are indicated. Several countries monitor successional stages and disturbances. Austria assesses succession in habitat 4080, Bulgaria tracks *Juniperus communis* recovery in habitats 5130 and 5210, and Germany uses expert assessments to monitor succession in habitat 40A0. Greece considers the evidence of primary or secondary succession in assessing habitat 4090. Generally, the methodologies considered in this analysis focus on limited biotic interactions.

Several functional gaps are apparent. Only one methodology measures Net primary production using remote sensing (Pescador et al., 2019), but no threshold values are indicated. Carbon sequestration indicators, like soil organic carbon (SOC), are generally absent. Expanding functional monitoring to these ecosystem functions, particularly for climate-sensitive habitats, is essential to enhance understanding of ecosystem processes, resilience, and ecosystem services in the face of environmental change.

Landscape

Landscape characteristics monitoring focused on metrics such as patch size, fragmentation, patch structure, and spatial distribution. Several methodologies address these characteristics, though the assessment methods are often not fully described.

Austria monitors fragmentation through patch intersections with infrastructure (e.g., ski slopes) in habitats 4060, 4070, and 4080, evaluating habitat connectivity and structural integrity. Belgium (Flanders) applies spatial cohesion criteria to assess clustering and patchiness in habitats such as 4010, 4030, and 5130, focusing on habitat continuity and conditions for landscape-level habitat connectivity. Bulgaria records new or disturbed patches across habitats such as 4030, 4060, and 4070, focusing on identifying disturbances that impact connectivity. Hungary measures landscape heterogeneity and isolation rates in habitats 4030 and 40A0, evaluating inner-landscape diversity that supports resilience. Italy uses landscape metrics to analyze patch size, distances, and spatial distribution across habitats such as 4030, 4060, and 4070, although the methods used need to be adequately described in the methodologies section. Lithuania monitors mosaic structure in habitats 5130 and 6530, highlighting patchy distributions that reflect habitat heterogeneity. It also detects ecotones within habitat patches, but no methods have been specified.

Other countries contribute unique landscape-monitoring approaches. Cyprus monitors vegetation patchiness to gain insights into habitat distribution in habitats such as 5330 and 5420. Germany tracks fragmentation indicators and bare-soil patches to gain insights into disturbance and connectivity in habitats 4060, 4070, and 5110. Finally, the Netherlands uses spatial condition metrics and GIS in habitats like 2310, 4030, and 5130, and Poland evaluates shrub fragmentation in habitat 40A0.

Other variables related to human activities, disturbance and degradation

Additional variables include anthropogenic activities, degradation and disturbance factors such as afforestation or tree planting, and inappropriate grazing and management practices, which are also relevant to evaluating habitat condition and are sometimes considered. Hungary, Germany, Austria, Spain, and Belgium (Flanders) include variables such as the presence or percentage of the surface affected by anthropogenic disturbances, including afforestation, trampling and browsing, and drainage. Grazing and mowing are monitored by visual assessment in several Member States (e.g., Austria, Czech Republic, Greece, Hungary, Italy, Lithuania, Latvia, Romania). Romania, Belgium, and Spain use methodologies to assess grazing impacts in habitats such as 4010, 4030, and 40A0. Other measurements focus on tracking target species linked to pollination and seed dispersal, e.g. in habitats 5110, 5130, 5410 and 5430 in Italy (Angelini et al., 2016). Common methods to evaluate these variables include periodic visual inspections and field surveys.

Several methodologies (e.g., from Germany, Greece, Hungary, Ireland, Italy, and Spain) include variables related to erosion, afforestation, anthropogenic disturbance, and other degradation factors. Despite their importance, fire regime metrics remain under-covered and are typically limited to qualitative assessments. Signs of degradation are identified using methods from the Czech Republic and measured on an intensity scale. Germany: based on some evaluations of habitat 5110, damage caused by *Cydalima perspectalis* or the fungal infection *Cylindrocladium buxicola* to the dominant plant *Buxus sempervirens*.

General remarks

European heathland and shrubland monitoring systems exhibit notable strengths and weaknesses. Key strengths include diverse monitoring methods, such as field surveys, visual inspections, expert assessments, and GIS-based spatial analysis, particularly for physical, chemical, and functional variables. Physical and chemical variables, particularly those related to soil characteristics like pH and nutrient ratios (e.g., C/N), are extensively monitored. Most of the methodologies analysed sufficiently cover compositional and structural variables. Some

MS (e.g., Austria, Belgium, and Germany) monitor fragmentation and disturbance indicators to assess habitat structure and resilience.

Weaknesses persist in the monitoring of functional ecosystem variables. Key processes such as primary productivity, seasonality, biotic interactions (e.g., pollination networks, seed dispersal), and carbon sequestration are generally under-monitored. The absence of robust data on primary productivity and carbon stocks (particularly organic soil carbon) complicates assessments of ecosystem health and carbon storage potential. Inadequate tracking of seasonal dynamics and phenology hampers our understanding of climate adaptation, especially in Mediterranean ecosystems. Limited information on biotic interactions and resource-use efficiency leaves critical ecological relationships and resilience indicators largely undocumented.

Fire regime metrics (e.g., frequency and intensity) are also scarce, undermining management efforts in fire-prone landscapes. Furthermore, the lack of data on successional stages restricts our ability to assess restoration progress. These monitoring gaps (especially acute in Mediterranean regions with high biodiversity) limit our understanding of the ecological processes underpinning resilience to climate change.

Endemic oro-Mediterranean heaths with gorse (4090)
© Dañiel,Goñi

Table 3. Variable groups included in the national methodologies available for the assessment of Heaths and Scrubs considered in this analysis

Variable group	AT	BE	BG	CY	CZ	DE	DK	ES	FR	GR	HU	IE	IT	LT	LV	NL	PL	RO	SK	SL
1. Abiotic characteristics																				
1.1 Physical state characteristics																				
Water availability																				
Soil characteristics																				
1.2 Chemical state characteristics																				
Soil pH & fertility (nutrients)																				
Organic matter content																				
Elements & contaminants																				
2. Biotic characteristics																				
2.2 Compositional state characteristics																				
Characteristic species																				
Species richness																				
Invasive species																				
Harmful species																				
2.3 Sructural state characteristics																				
Vertical structure																				
Horizontal structure																				
Microhabitats																				
2.3 Functional state characteristics																				
Primary production																				
Successional stages																				
Disturbance indicators																				
3. Landscape characteristics																				
Patch size																				
Fragmentation																				
Mosaics																				

2.2 Definition of ranges and thresholds to obtain condition indicators

Countries use a variety of thresholds and reference levels to assess habitat condition, but more information is needed about how these thresholds and ranges are set. The table in Annex presents examples of thresholds for different variables in the methodologies considered in the analysis.

Ranges are rare for physical variables, except for the Flemish methodology, which defines favorable reference ranges for all abiotic variables (Van Calster et al. 2020). Physical thresholds are primarily established by a few countries, such as Denmark, Spain, and Ireland, indicating their application is limited and mainly focused on soil health and hydrology. For chemical variables, thresholds are generally defined more consistently, for instance, regarding chemical elements present in the soil, C/N ratio (e.g., Belgium-Flanders for habitats like 4010 and 4030), Nitrogen deposition (e.g., Belgium-Flanders and Denmark), soil pH (e.g., France, Denmark and Spain), and electrical conductivity of soil (e.g., Spain including 4020-4090, 5110 and 5120).

For compositional variables, thresholds are often used to assess species diversity and abundance, including the presence of indicator species (e.g., in methodologies available in Ireland and Poland). Several methodologies measure the number of characteristics, key species, or typical species in the monitoring plot using reference lists and abundance benchmarks to assess habitat conditions. Typical and key species presence is evaluated across countries such as Austria, Bulgaria, Ireland, and Germany for several habitats. Species Richness and Abundance are used in Spain (ES), focusing on perennial species and key functional types for habitats 4020–4060 and 5110–5120, but thresholds are not provided. Harmful indicator species are assessed in Ireland for habitat 5130, establishing that minimal presence of such species indicates degradation. Poland applied thresholds in habitats like 4060 and 4070, focusing on species dominance as an indicator of habitat health.

Structural variables commonly rely on thresholds for vegetation height and canopy cover (e.g., a specific percentage of characteristic species cover indicates good condition) and for successional stages. Countries like Ireland, Germany and Denmark establish thresholds —for instance, for habitat 4030, for which a favourable status requires shrubs between 0.5–1.0 m in height, with canopy cover exceeding 70%, or for habitat 40A0, where height and density thresholds are tailored to specific growth phases. Shrub and herbaceous layer coverage is also proposed in Ireland, Poland, and Spain, considering thresholds of at least 50% shrub cover for good condition in habitat 4010 and 30% or more for habitat 4030. Regarding the growth phases of shrubs (e.g., *Calluna vulgaris*), Ireland and Austria consider that habitat 4030's favorable status requires a balanced proportion of juvenile, mature, and senescent shrubs.

Functional thresholds are less commonly applied than structural or compositional variables, but they do occur in specific habitats and contexts. Functional thresholds are typically qualitative and focus on indicators such as successional stages, leaf litter, grazing impacts, erosion, or regenerative capacity. Regarding thresholds for assessing succession, for instance, the methodology available in Austria for habitat type 4080 sets a reference value for good condition, where little or no succession by mountain pines, green alders, or other forest types is detected in the monitoring plot. Hungary considers for balanced dynamics of leaf litter accumulation and decomposition in habitats such as 4030, 40A0, and 5130. Romania in habitat 4030, where grazing intensity is rated from "none" to "intense". Greece considers the absence of significant erosion or overgrazing required for favorable condition in habitats in 4060 and 4090.

Landscape thresholds, vital for assessing connectivity at broader scales, need further development. Belgium-Flanders applies specific thresholds for evaluating the spatial context of habitats, focusing on the minimum area and spatial cohesion to ensure habitat connectivity and integrity. The assessment includes two criteria: the A criterion, which evaluates habitat cluster size, and the B criterion, which examines the size of specific habitat patches. For 4010, favorable conditions are achieved if habitat clusters are ≥75 ha and specific patches are ≥5 ha. Similarly, for 4030, clusters must be ≥50 ha and patches ≥5 ha, whereas for 5130, clusters must be≥75 ha and patches ≥5 ha. These thresholds illustrate Belgium's approach to maintaining spatial cohesion and ensuring the ecological stability of key habitats. Austria, Bulgaria, Germany, and Poland have established explicit thresholds for spatial metrics such as fragmentation, patch structure, and spatial distribution, focusing on their impact on habitat functionality. Austria applies thresholds to habitats such as 4060, 4070, and 4080, with favorable conditions requiring no infrastructure fragmentation (A: Low), while M (B) and high (C) fragmentation indicate increasing habitat degradation. Bulgaria evaluates fragmentation across diverse habitats, including 4030–4090 and 5130, 5210, where favorable conditions require minimal new fragmentation and maintained connectivity. Germany focuses on fragmentation as a disturbance indicator in habitats such as 4060 and 4070, with thresholds defining favorable status (A) as no fragmentation, while M (B) and significant (C) levels indicate growing impacts from transport infrastructure. Poland assesses the spatial structure of bushes in 5130, where favorable conditions (FV) allow no or slight fragmentation, whereas M (U1) and severe (U2) fragmentation reduce habitat functionality. These thresholds emphasize the importance of minimizing fragmentation and maintaining connectivity to preserve the ecological integrity of these habitats.

The analysis of national methodologies highlights the need for standardised thresholds, especially for physical, chemical, functional, and landscape variables, where quantitative benchmarks still need to be developed. This lack of detailed thresholds for specific indicators creates gaps in understanding habitat responses to environmental pressures, potentially limiting conservation effectiveness. Expanding and unifying thresholds in these areas could significantly enhance the comparability and consistency of habitat monitoring across Europe, supporting more robust, data-driven conservation efforts.

2.3 Aggregation methods at the local scale

An overall assessment result at the local scale, i.e., at the monitoring plot/station level, requires integrating results for each measured abiotic and biotic variable at that location. Different methodologies are used across the analysed methodologies from the various Member States. It should be reminded that assessing habitat structure and function requires considering two main categories: good and not-good condition. Ultimately, it is necessary to know the proportion of the habitat area in ‘good’ and ‘not-good’ condition. However, in the national methodologies analysed, many MS use three categories (good, medium, low, or favourable, unfavourable, bad) both to establish thresholds for the measured variables and to conduct the overall assessment at the local scale.

Some aggregation methods are common across several countries, but the details and the integration approach vary significantly. The main approaches for aggregating variables measured at the local scale include the following rules: the worst-score rule (the "one-out-all-out" rule), additive or hierarchical arithmetic operations that can weight variables, conditional rules, and majority rules. Some examples of the methods used are described below.

Some national methodologies (e.g. those available from Austria, Germany and Luxembourg) address the assessment of habitat condition using three groups of biotic variables related to composition (e.g. completeness of the habitat typical species composition, presence of characteristic species), structure (e.g. coverage of particular species or groups, typical structural elements) and functions or influencing factors that are associated with disturbance/alteration indicators. Each variable can be assessed in three categories. In Germany, for instance, these categories correspond to excellent conservation status (A), good conservation status (B) and medium to poor conservation status (C). An accounting matrix summarises the results of evaluating individual variables into an overall assessment for each sample plot. The overall result is obtained by applying the following rules: 3xA=A, 3B=B, 3C=C; 2A+1B=A; 2A+1C=B; 2B+1C=B; 1A+1B+1C=B.

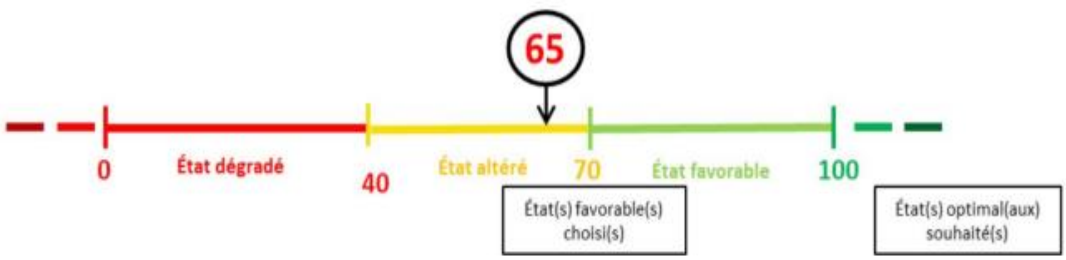
In the methodology applied in Belgium-Flanders for the period 2013-2019, the variables used in the assessment were classified as: "Very important" (which hinders the favourable condition of the habitat in the long term, requiring more than ordinary efforts to remedy), and "Important" (whose condition is nearly or entirely controlled by management). Once each variable was assessed according to the established thresholds, the following decision framework was used:

- If at least one Very Important indicator scores unfavourable, the one-out-all-out rule applies, and the overall assessment of the spot is unfavourable.
- If none of the Very Important indicators score unfavourable, then a second step is applied:
  - If half or more of the indicators score unfavourable, the overall assessment of the spot is unfavourable.
  - If less than half of the indicators score unfavourable, the local assessment of the spot is favourable.

In the methodology applied in Bulgaria (MOEW, 2013), a summary assessment of the local condition is obtained from the evaluation of the various variables using the following rules: the assessment is favourable for structure and function when all variables are scored as “favourable” or when all the variables are “favourable” but a maximum up to 25% of the variables have been assessed as having insufficient information available. If the assessment is “unfavourable-bad for just one variable, the overall assessment becomes unfavourable-bad. Unfavourable – inadequate is determined by any other combination.

In the methodology available in France for habitat types 4010 and 4020 (Mistarz and Grivel, 2020), each variable (indicator) is given a score on the plot/polygon scale, which can be positive, negative, or zero. The sum of the scores is then subtracted from 100, and the result is placed on a scale from 0 to 100, with higher scores indicating the best condition. A threshold value of 70 is used to determine good condition, but it is acknowledged as arbitrary.

Figure 1. Aggregation method applied to all habitats in France



Greece and Cyprus apply the assessment at the local level by considering separately the following parameters: a) typical species (recording the presence, abundance and vitality of each species); b) specific structures and functions in good condition (as listed in a form that is specific for each habitat type. The condition of a typical species is assessed based on its cover (High, Medium, Low) and vitality (1, 2, 3). For structure and function, the protocol defines specific variables for each habitat type and their thresholds or ranges for favourable condition, to be checked at each sampling site. The final assessment is determined by the % of variables that have passed the range set for favourable condition: > 50% result in favourable overall assessment, >25-50% lead to unfavourable-inadequate condition, and 0-25% for unfavourable-bad condition. The results of the evaluation of typical species and specific structure and function are then integrated into a final result: favourable only when both parameters are assessed as favourable, and in bad condition when at least one is in bad condition.

In the methodology available ~~for~~ Ireland for habitat types 4010 and 4030 (Perrin et al. 2014), the overall assessment at the local level (monitoring plot) is based on the percentage of variables that meet a threshold for good condition. When monitoring stops with no failed criteria, the stop automatically passes at the stop level. When monitoring stops have failed one or more criteria, expert judgement of the ecological condition of those stops may be employed to reassess whether any of those stops might legitimately be permitted to pass, for example, if there has been a marginal failure of a single criterion. In any other case, the stops are deemed to have failed.

2.4 Aggregation at the biogeographical scale

Overall, most MS follow the recommendations from the Art. 17 reporting guidelines for 2013-2018, which establish that "if 90% of habitat area is considered as in 'good' condition, then the status of '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 have also considered aggregating variables at the biogeographic level to identify which variables determine the unfavourable status (e.g., in Belgium-Flanders, see Paelinckx et al. 2019). However, it must be stressed that reporting habitat structure and function under Article 17 requires determining the proportion of the habitat area in good or poor condition, which implies the need to provide valuable data aggregation.

2.5 Selection of localities

Although selection criteria may vary across countries, most select monitoring localities based on habitat representativeness, spatial distribution, and ecological significance. In general, selecting appropriate localities for the assessment requires knowledge of the areas of habitat occurrence in the country, which is not always available or available with sufficient detail.

Most MS aim to achieve representative coverage by selecting localities that reflect different environmental conditions, ecological gradients, management, and protection conditions within each habitat. The final selection is often made based on some criteria. The main approaches and criteria applied in the methodologies considered in this analysis are described below.

Ecological variation and relevance: Some countries attach great importance to capturing the environmental variation and the habitat's relevance. In the methodology available in Belgium (Flanders), the appropriate assessment scale is primarily determined by 'ecological relevance', considering the need to reflect local variation within a habitat site and across several successional stages for some habitat types, among others (Oosterlinck et al., 2020). In Ireland, sites for assessment of Atlantic wet heaths (4010) were selected from a comprehensive list of sites identified as candidates for an upland habitats' monitoring network based on criteria such as area, number of upland habitats, representativity, proportion of site composed of upland habitats, and presence of habitat features which are either rare or particularly important in an international context (Perrin et al., 2014). In Hungary, selection is based on several factors (distribution, rarity, importance for nature conservation, and Hungary's role in habitat conservation). Altogether, ten sampling sites were proposed for habitat 4030, 62 for habitat 40A0, and 33 for habitat 5130. Not only "typical" plots of the habitats to be mapped, but secondary or damaged localities are included outside and inside the 2000 network.

Regular or random stratified sampling: localities or stations for monitoring are selected using habitat maps, GIS, and a grid to determine random sampling locations. In Spain, based on detailed mapping of the distribution of the habitat type in question, its occupation area, and the protection areas where it is present, the sampling points and their geographic coordinates will be selected through random stratified sampling (Pescador et al., 2019b). Specific areas of particular interest for monitoring may also be included for some habitat types, as considered appropriate, and the reasons specified. As far as possible, plots will be chosen to ensure adequate access and to avoid ecotones or transition zones between two or more habitat types. In Belgium (Flanders), stratified samples are established using habitat maps superimposed on a master sample of 32 m x 32 m via the GRTS algorithm. The master sample forms the basis for selecting a desired number of sample points within the polygons of a given habitat type (Westra et al., 2014). In Romania, the selection of monitoring localities considers the area occupied by each habitat and its geographic distribution. Stratified sampling for habitats 4030, 4080, 40A0, and 40C0*and clustered adaptive sampling for habitats with a small distribution area are suggested. Because of the vast area occupied by habitats 4060 and 4070, systematic sampling utilizing the national grid designed for the National Forest Inventory will be employed (Deak et al., 2014).

Expert Judgment and Spatial Analysis: This approach leverages ecological expertise and spatial insights to identify ecologically and geographically representative sites within diverse habitat structures. Poland uses expert knowledge and spatial analysis to select sites for habitats such as 4010, 4030, and 4070, aiming to include ecologically significant and spatially diverse locations. All known localities should be monitored for some habitats (e.g. 4060, 4080) (Świerkosz, 2012). Germany also selected the monitoring locations for some heath habitats (4060, 4070) in the alpine region based on expert judgement and available data. For other habitats with a small area in a biogeographical region, all areas of occurrence shall be monitored (BfN, 2017). In Romania, the locations of sample sites for each habitat type will be identified using maps of their potential distribution compiled from multiple sources, including aerial photo interpretation (Deak et al. 2014).

Permanent Plots for Long-Term Monitoring: Permanent plots provide reliable, consistent data over time, allowing for long-term ecological insights. For instance, 147 permanent monitoring plots were selected in the Czech Republic in 2005 for monitoring heaths (including 51 PMP for 4030, 31 for 4060, 5 for 4070, 11 for 4080 and 46 for 40A0). The selection was made by experts considering only representative or characteristic occurrences of the habitats (Vydrová & Lustyk, 2014). Similarly, Denmark uses pre-selected sample sites within its NOVANA programme to monitor Northern Atlantic wet heaths (4010), ensuring consistent site-specific monitoring across the years (Fredshavn et al, 2022).

Proportional Plot Density Based on Habitat Area: For countries with large habitats, monitoring plot density is adjusted proportionally to the habitat's size. Hungary employs this method, increasing plot density in expansive habitats such as 4030 and 40A0 to maintain representative coverage. This criterion ensures that larger habitats are not undersampled, maintaining statistical representation across varying habitat sizes.

Some countries lack structured criteria for selecting localities for monitoring, indicating an area for improvement. The diversity of criteria reflects regional adaptations to ecological conditions, but greater standardisation could enhance consistency and comparability across European habitat-monitoring frameworks.

2.6 General monitoring and sampling methods

All MS use fieldwork for the monitoring. Relevant elements of existing monitoring schemes for habitat assessments are described below.

Form and size of sampling plots

The methodologies applied across Europe for monitoring heath and scrub habitats demonstrate a balance between standardized protocols and flexibility to adapt to local ecological and logistical conditions. Countries like France, Ireland, and Spain focus on smaller plots for detailed assessments, whereas Poland and Latvia usually employ transects to capture spatial heterogeneity. Permanent monitoring locations in Czechia, Hungary, Romania, and Slovakia provide a framework for long-term data collection. These approaches ensure that monitoring reflects habitat complexity and supports effective conservation planning.

In France, 10 m x 10 m plots are used for monitoring habitats such as 4010. These plots can be adjusted in shape (circular, rectangular, or linear) to fit the shape of the polygon being assessed. Such flexibility ensures that the sampling area represents the habitat's floristic composition and environmental characteristics, including slope, exposure, and microtopography (Mistarz & Grivel, 2020). Similarly, Denmark uses circular plots with a 5-meter radius to record species composition, structural parameters, and environmental factors, such as soil and water conditions. This approach ensures comprehensive coverage of habitat characteristics (Fredshvan et al., 2022). Ireland employs 2 m x 2 m monitoring plots for habitats such as 4010 and 4030, assessing variables within the plot and in the surrounding habitat area, which extends 50–100 m around the plot. For habitat 5130 (Juniper formations), 5 m x 5 m plots are used to evaluate structural and functional variables (Perrin et al., 2014; O'Neill et al., 2018a,b). In Spain, a stratified random sampling design is recommended. This method includes a 10 m x 10 m sampling plot within a 30 m radius circular plot and linear transects spaced 2.5 meters apart. This combination of nested and transect-based sampling allows for detailed vegetation and structural assessments across habitat patches (Pescador et al., 2019a).

Poland adopts a unique approach using 200 m x 10 m transects. These transects are located using GPS and can be adjusted in size if necessary. Phytosociological relevées are recorded at each transect's beginning, middle, and end to capture variation within the habitat (Mróz, 2010). In Latvia, transects measuring 200 m x 10 m (2000 m²) are used for habitats such as 4030. These transects are complemented by two 25 m² vegetation plots (one subjectively chosen in the best typical part of the habitat and one randomly placed), with a 1 m² subplot for species richness. For 5130, shorter 50–100 m transects are used, depending on the polygon size, to balance spatial coverage and habitat representativeness (DAP, 2023).

In Czechia, permanent 25 m² plots are used for habitat 4030, with emphasis on floristic composition and environmental variables, making them suitable for long-term monitoring (Vydrová & Lustyk, 2014). Hungary uses fixed 400 m² permanent monitoring localities (TML), typically 20 m x 20 m, with six 0.5 m² plots placed diagonally within the TML. This design ensures systematic sampling while allowing flexibility for fragmented habitats (Horváth et al., 2021). Romania uses sampling plots ranging from 50–500 m², with smaller plots (e.g., 50 m²) used in extreme cases for habitats such as 4080 or 4030. This flexibility allows monitoring in challenging or fragmented conditions (Deak et al., 2014). Slovakia adopts a broader monitoring scale, establishing permanent monitoring locations ranging from 0.1–5 ha, assessed along zig-zag transect lines. This approach ensures extensive spatial coverage while capturing essential habitat variables (Saxa et al., 2015).

Sample size: number of plots

Some of the methodologies available from the MS provide information about the number of monitoring localities. However, do not usually give the exact number of plots per habitat type to be surveyed. Some MS provide instructions or recommendations for calculating this number using a statistical approach. For instance, the methodology available in Spain suggests estimating the sample size using a formula that analyses the relationship between sample size and the minimal detectable effect size for a given significance level α and a power π. Thus, for example, to estimate the proportion of the habitat in bad condition with a precision of 5%, the number of plots needed would be 384. A minimum of 40 sampling plots per habitat type and biogeographic region could be considered to achieve a compromise among statistical power, precision, and sampling effort. This number represents approximately a precision of 0.15 when estimating the proportion of unfavourable habitat type from a discrete number of observations or plots. It could correspond to the habitat types with the smallest area in the territory, but the number could reach a maximum of 400 plots in the habitat types with the most significant area (Pescador et al., 2019a). The methodologies available from Belgium-Flanders and Germany suggest similar statistical methods for calculating the minimum sample size (Westra et al., 2022; Sachteleben and Behrens, 2010).

Sampling period

Most fieldwork is performed during spring or summer, during the growing and flowering seasons. There are some differences in the periods suggested in the national methodologies (e.g., from May to October in DK and from June to July in Italy and Latvia), but these are not considered relevant.

Monitoring frequency

Most countries use the monitoring frequency requested for reporting under Article 17 of the Habitat Directive, i.e., 6 years. However, some MS have drawn up a calendar plan for habitat monitoring over 12 years (e.g., Latvia), with observations carried out at least three times in each monitoring plot and at each monitoring location. Observations should be conducted in 16 monitoring squares every 12 years.

National monitoring programmes, such as Denmark's NOVANA and Ireland's National Survey of Upland Habitats (NSUH), ensure standardised, consistent monitoring across various habitats. These programmes regularly monitor heath and scrub habitats, such as 4010, 4030, and 5130, enabling detailed data collection and tracking of habitat changes over time. The frequency of monitoring must ensure that data remain up to date and allow detection of changes and trends in habitat conditions.

While many countries apply structured, consistent protocols, gaps exist in some countries that lack detailed protocols. This limits standardisation across Europe, though overall, the diversity in sampling protocols and locality selection contributes valuable ecological insights. Harmonising these practices, especially in site selection and sampling frequency, could enhance data quality and cross-country comparability in habitat monitoring.

2.7 Other relevant methodologies

The following studies showcase diverse methodologies, ranging from field sampling to remote sensing, for evaluating shrubland habitats in different regions of the world. These approaches provide valuable insights for implementing standardized and adaptable monitoring frameworks within the European Union for the management of heathlands and shrublands.

Field sampling methods in the Chihuahuan Desert

Godínez-Alvarez et al. (2009) evaluated three field sampling methods—line-point intercept, grid-point intercept, and ocular estimates—for monitoring vegetation cover and composition in shrubland ecosystems of the Chihuahuan Desert, comparing them based on data interchangeability, precision, cost, and the ability to generate multiple indicators. Results show that line- and grid-point intercept methods yield similar estimates of species richness, both of which are lower than ocular estimates. However, they provide higher and more precise estimates of foliar cover. Time requirements for all methods were similar, despite point-based methods assessing more canopy layers.

Biodiversity Metrics for Ecosystem Integrity

Helm et al. (2015) propose an innovative approach for assessing the integrity of shrubland ecosystems by differentiating between two components of biodiversity: characteristic and derived diversity. Characteristic diversity refers to species that belong to a habitat-specific historical species pool, representing the natural and typical state of the ecosystem. Derived diversity, conversely, includes species introduced due to human impact or environmental changes, such as non-native species or native species from other habitats. The authors introduce the Favourable Conservation Status Index (FCSi), a metric based on the log ratio of characteristic to derived diversity, as a tool for quantifying the ecological condition and conservation needs of habitats. This index is particularly relevant for identifying areas requiring conservation efforts and evaluating restoration success. By integrating ecological history and current biodiversity patterns, this methodology provides a replicable framework for monitoring shrubland condition, aligns with global biodiversity targets, and offers actionable insights for habitat management and restoration.

Wildfire Monitoring in Australian Shrublands

Australia's Bushfire Monitoring Program is a crucial initiative that tracks the impacts of wildfires on shrublands and other terrestrial ecosystems (Clarke et al. 2019). Managed by various organisations, including government agencies, universities, and conservation groups, this program aims to understand the effects of fires on biodiversity, habitat structure, and ecosystem resilience. Researchers collect information on affected flora and fauna, fire severity, and ecosystem recovery rates using satellite imagery, drones, field surveys, and historical fire data analysis. The findings, published in regular reports, are essential for developing fire management and conservation policies and educating the public on the importance of shrublands and the need to protect them. This Monitoring Program employs a variety of variables to track the impacts of wildfires on shrublands and other terrestrial ecosystems (Lindenmayer et al., 2025). These variables include vegetation metrics such as cover, species composition, regeneration rates, and habitat structure. Faunal diversity, abundance, and post-fire habitat quality are also monitored. Soil properties (both physical and chemical) and erosion rates are evaluated. Climate and meteorological variables, such as temperature, humidity, precipitation, and wind patterns, are recorded to understand their influence on fire behaviour and recovery. Fire severity variables, such as burnt area, fire intensity, and damage severity, are measured alongside landscape-level metrics, such as habitat fragmentation and fire patterns. Advanced technologies, including satellite imagery, drones, and field sensors, are utilised to obtain comprehensive, real-time data. This multidimensional approach enables scientists and managers to effectively assess fire impacts and develop informed strategies for ecosystem recovery and conservation.

Monitoring Shrubland Integrity in Mediterranean Ecosystems

Lawson and Keeley (2019) present a monitoring framework for assessing shrubland community integrity in California's Mediterranean-type ecosystems, addressing the need for accessible, scalable tools to monitor these biodiversity-rich yet threatened landscapes. The framework uses simplified metrics, such as the proportion of shrub cover to non-native grasses, shrub density, and species diversity, to classify ecosystem integrity and capture disturbance impacts. It operates across three spatial scales—landscape, habitat patches, and transects—and includes a two-tiered sampling system combining rapid visual assessments with detailed plot-based monitoring. A pilot phase ensures the refinement and validation of thresholds and methods. The framework integrates vegetation data with fire history, vulnerability overlays, and conservation priorities, facilitating decision-making and cost-effective management. Designed to engage diverse stakeholders, it supports collaboration among policymakers, land managers, and scientists, promoting informed strategies for managing and conserving these critical ecosystems. This initiative demonstrates how scientific rigour and simplicity can be combined to address complex environmental challenges.

Remote Sensing approaches

Schmidt et al. (2017) present a novel approach to adapting Natura 2000 field guidelines for assessing the conservation status of Calluna vulgaris-dominated heathlands using remote sensing. Integrating UAV data, hyperspectral imagery, and field samples, the study mapped three key quality layers: Calluna coverage, stand structural diversity, and co-occurring vegetation. These layers were combined into RGB visualizations and discrete habitat quality classes. The results showed a strong correlation between remote sensing-derived data and field measurements. The study highlights the advantages of remote sensing, including enabling continuous habitat-quality mapping. While the method demonstrated transferability to similar habitats and proved a valuable complement to field-based assessments, the authors emphasise the need to adapt field guidelines to leverage remote sensing capabilities fully. Along the same lines, the same authors (Schmidt et al. 2018) developed a method that combines Sentinel-1 (SAR) and Sentinel-2 (multispectral) satellite data to assess habitat quality. Both studies align with Natura 2000 conservation requirements, offering an efficient, scalable remote-sensing-based tool for habitat monitoring and management.

Haest et al. (2017) present an innovative multi-step framework for mapping NATURA 2000 heathland habitats and assessing their conservation status using imaging spectroscopy. The proposed method comprises three main steps: hierarchical classification of land/vegetation types (LVT) based on spectral and field data; spatial reclassification to convert LVT maps into patch maps by life form; and identification of NATURA 2000 habitat types and conservation status parameters at the patch level. The study achieved high classification accuracies using supervised learning techniques, such as Linear Discriminant Analysis and feature selection algorithms. Conservation status indicators, including tree, shrub, and grass cover, were accurately derived and strongly correlated with independent field data. This approach integrates conservation parameters required by the Habitats Directive, such as ecological quality and pressures, ensuring practical applicability for local and national managers. Additionally, the study highlights the potential to address the challenges posed by fragmented heathlands, which are threatened by nitrogen deposition and the abandonment of traditional practices. The method generates maps and statistics consistent with field-based workflows, demonstrating how imaging spectroscopy can complement or replace conventional field methods for monitoring and conserving protected habitats.

Requena-Mullor et al. (2018) proposed a remote sensing-based approach to monitor the conservation status of high-mountain shrublands in Southern Spain by analyzing ecosystem functioning. This methodology relies on vegetation indices derived from satellite imagery, such as the Enhanced Vegetation Index (EVI), to capture key dynamics of primary productivity and ecosystem phenology. The approach consists of four main steps. First, reference sites and habitat patches are selected. Reference sites are identified based on expert judgment, focusing on patches with optimal composition and structure, characterized by species diversity and canopy cover. Second, the ecosystem functioning of these habitats is described using two functional descriptors: the annual mean EVI (a proxy for mean primary production) and the seasonal coefficient of variation of EVI (an indicator of canopy seasonality). Third, the functional descriptors are arranged in a two-dimensional space to calculate the distances of evaluated patches from reference sites, reflecting deviations from optimal functional states. Finally, the habitats are categorized into three conservation status levels—favourable, unfavourable-inadequate, or unfavourable-bad—based on mean distance, following the guidelines of the European Habitats Directive. This approach offers a quantitative, spatially explicit, and reproducible method to assess the functional dimension of habitat conservation status. It addresses challenges in implementing the Habitats Directive, enabling long-term monitoring and early detection of environmental changes.

Cabello et al. (2018) propose a satellite remote sensing-based approach to strengthen the implementation of the Habitats Directive by incorporating ecosystem functional indicators into conservation status assessments. The methodology focuses on using satellite-derived products—such as estimates of primary productivity, evapotranspiration, and other key ecological processes—to characterize functions relevant to habitat resilience and long-term maintenance. These indicators are linked to reference conditions and spatial–temporal change detection, enabling the identification of deviations from optimal functional states and the anticipation of climate change or anthropogenic impacts. The study emphasizes the need for habitat-specific indicator selection, alignment between ecological and satellite observation scales, and the production of clear, actionable metrics—including classification systems such as the Directive’s “traffic light” scheme—to facilitate their uptake by managers and policymakers. In addition, the authors highlight the importance of fostering stronger dialogue and collaboration between the scientific community, conservation practitioners, and decision-makers to ensure that technical advances in remote sensing are effectively translated into practical, policy-relevant tools for habitat monitoring and management.

Other examples of remote sensing-based approaches to monitor heathlands and scrublands are indicated in Table 6.

2.8 Conclusions

The following conclusions address the variability in current practices, highlight common strengths and gaps, and outline preliminary recommendations to harmonize European methodologies and ensure cohesive, effective habitat conservation. The analysis of national methods for assessing and monitoring heath and scrub habitats across 20 EU countries highlights a diversity of approaches, reflecting regional ecological and logistical conditions. Overall, the methodologies showcase strengths in capturing compositional and structural variables but reveal significant gaps in functional and landscape assessments. Harmonization of methods, especially for thresholds and functional monitoring, could improve cross-country comparability and the robustness of habitat condition assessments.

General strengths and weaknesses: Physical and chemical variables are frequently assessed, with soil characteristics (e.g., pH, C/N ratio, organic matter) and hydrological conditions being common metrics. However, gaps remain in monitoring temperature, radiation, and carbon sequestration, limiting insights into climate-sensitive processes. All countries consider species richness, dominance, and the presence of invasive species, but usually only for plants. Some include indicator species or species indicative of trophic enrichment. Methods such as vegetation relevés and transects are widely used, but thresholds for key variables are often undefined. Vertical and horizontal habitat structure, including shrub height and canopy cover, is consistently assessed across countries, providing insights into habitat maturity and disturbance. Few methodologies track age structure or growth stages in detail, though Ireland and Austria offer some notable examples. Functional variables are less frequently monitored, focusing primarily on regeneration, recruitment, and disturbance indicators. Functional gaps, such as tracking primary productivity or carbon cycling, are common. Countries like Belgium and Austria include spatial metrics such as fragmentation and patch size, highlighting the importance of connectivity. However, detailed methodologies for these variables are less widespread. Regarding sampling approaches, countries vary in plot size, sampling design, and monitoring frequency. While some, like Spain, use statistically driven stratified random sampling, others rely on expert judgment or permanent plots for long-term monitoring.

Variability and heterogeneity in monitoring: There is a significant imbalance in the type of variables used. The most commonly used by countries are those that correspond to habitats' compositional and structural characteristics. Functional variables are rarely addressed beyond recruitment, successional stage and disturbance indicators. There are some interesting efforts to monitor abiotic variables, although there is considerable variability in how physical and chemical variables are monitored for heaths and scrubs. While some countries (e.g., Belgium, Denmark, Spain) have designed highly detailed monitoring systems that include key abiotic variables (e.g., soil properties, hydrology, geomorphology), some other national methodologies do not sufficiently cover those variables. Addressing these disparities is critical to creating a cohesive, balanced monitoring framework that accommodates diverse European landscapes.

Redundancy in the metrics used across countries to assess the same variable: Different countries use different metrics to assess the same variable, thus representing common monitoring strategies. This variability in metrics is especially profuse in the case of structural and compositional variables. For example, species cover, number of diagnostic species and species occurrence are used to assess habitat composition (both native and invasive species). Vegetation height and vegetation layer cover are used to assess vertical structure. Variables of this type should be grouped for generalisation based on the variable they are intended to control.

Lack of consideration of characteristics or typical animal species: In most Member States, habitat assessments focus predominantly on vascular plant species, overlooking animal species that could also serve as typical species. This omission limits the ecological representativeness of the evaluations, especially in habitats where animal communities play key functional or structural roles (e.g. pollinators, herbivores, ground-nesting birds). This gap merits specific attention and should be addressed in future harmonisation efforts.

Common monitoring aspects: Analysis of methodologies reveals common methods for measuring abiotic and biotic variables, supported by widespread practices such as visual inspection, GIS sensors, and soil sampling. These approaches create a solid foundation to work for comparative monitoring across nations. However, gaps remain in habitat representation, with certain habitat types (e.g., wet heaths) being under-monitored. These gaps highlight the need to further harmonize monitoring efforts, ensuring more balanced attention and adapted methodologies for specific habitats.

Promotion of good practices in habitat monitoring: Good practices in monitoring should be defined by standardised, consistent, and adaptable methods that generate high-quality, comparable data. This practice must include multidimensional variables (physical, chemical, biological, and functional) to assess habitat structure and functions. Additionally, we must adapt methodologies to specific regional conditions, such as water stress in Mediterranean regions or cold tolerance in the Boreal region. Integrating advanced technologies such as remote sensing, GIS, and drones enhances accuracy and coverage while reducing costs. To maximise the impact of monitoring efforts, we should provide transparent, accessible data to all stakeholders, foster open collaboration, set clear benchmarks, and promote systematic sampling protocols, as shown in the methodologies from Belgium, Denmark, and Hungary.

Addressing shortcomings and gaps: Significant gaps in monitoring functional variables essential for ecosystem resilience, including primary productivity, seasonality, and carbon sequestration, remain. Such variables are crucial for assessing ecosystem health, especially under climate stress. Furthermore, the lack of fire regime metrics (e.g., frequency, intensity) limits understanding of fire-prone habitats. At the same time, inconsistent tracking of grazing impacts and successional stages restricts insights into habitat regeneration. Addressing these gaps through gathering consistent data on resilience and land management practices is essential to improving monitoring.

Need for harmonization of methodologies: Harmonizing habitat monitoring across Europe poses several challenges, including ecological diversity, differences in national resources, and the lack of common thresholds and reference values. Countries vary in their access to technology and infrastructure, which limits their ability to implement high-precision methods uniformly. Furthermore, policy priorities differ, leading to varying focus areas that may not align with a standardised approach. Harmonisation should establish clear thresholds for critical variables and integrate functional metrics and advanced technologies to improve monitoring precision. This approach must, however, be flexible, accommodating regional variability and technical capacities.

Learn from other methodologies to complement and improve the methods used in EU Member States: Integrating methodologies from international programs could help gather standardised, high-quality data to address critical issues such as climate change, land use, biodiversity, and biogeochemical cycles. For instance, field sampling methods such as line-point and grid-point intercepts can yield reliable estimates of vegetation cover and composition while remaining interchangeable with other methods. Incorporating Biodiversity Metrics for Ecosystem Integrity to emphasize the value of distinguishing between characteristic and derived biodiversity can quantify ecosystem integrity by linking historical ecological conditions with current patterns. Australia's Bushfire Monitoring Program, as outlined by Clarke et al. (2019), showcases a multidimensional approach combining satellite imagery, drones, and field surveys to track vegetation recovery, biodiversity impacts, and fire severity. This comprehensive methodology provides insights for assessing the resilience of shrublands under fire-prone conditions, which could be adapted to European contexts. Lawson and Keeley (2019) propose a scalable, stakeholder-inclusive monitoring framework for shrublands integrating spatial data with fire history. Finally, remote sensing studies (e.g., Schmidt et al., 2017; Haest et al., 2017; Requena-Mullor et al., 2018) illustrate the potential of UAVs, satellite imagery, and imaging spectroscopy to map habitat quality, structure, functioning, and conservation status. These methods provide scalable, cost-effective alternatives to field surveys while maintaining strong correlations with ground-truth data. Remote sensing can complement traditional methods, enabling continuous monitoring and better coverage of extensive or remote shrublands.

Alpine heaths (4060). Vysoké Tatry, Slovakia.
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3. Guidance for the harmonisation of methodologies for assessment and monitoring of habitat condition

Harmonising methodologies for assessing and monitoring habitat condition in Heaths and Scrubs represents a significant challenge due to the diversity of ecosystems associated with these habitats and the varied approaches currently used by EU Member States. This harmonisation requires the development of integrative methods capable of capturing the complex biological, physical, and chemical characteristics that define habitat in good condition and underpin the provision of ecosystem services. Key steps toward effective harmonization include consistency, transparency, adaptability, and collaboration. Consistency in using standardised protocols and indicators is crucial to ensure data comparability across countries and biogeographical regions, while transparency in documenting methodologies and data collection enhances replicability. Adaptability is necessary to tailor these methods to specific regional or habitat conditions while maintaining core standards. Collaboration with experts and stakeholders is essential for developing scientifically rigorous and feasible methodologies for assessing conservation goals and available resources and expertise.

Establishing a robust monitoring framework to collect baseline data, select sensitive indicators that accurately reflect habitat condition, and implement consistent data-collection methods—including field surveys, remote sensing, and citizen science initiatives—is critical. Data management systems must be robust and capable of supporting adequate storage, analysis, and sharing. Clear data interpretation and reporting formats are essential for communicating findings to policymakers and stakeholders. Before large-scale implementation, methodologies should undergo pilot testing to ensure their reliability and relevance. Finally, capacity building and continuous monitoring and evaluation are necessary to refine methods and adapt them to evolving needs.

3.1 Selection of condition variables, metrics, and measurement methods

To standardize the assessment and monitoring of habitat condition accounts at the EU level, it is essential to identify a concise set of relevant variables that can serve as condition indicators. A key challenge in ecosystem assessment lies in selecting metrics that capture the most pertinent ecosystem characteristics and address essential aspects of ecosystem quality (Czúcz et al., 2021; UN, 2021).

Variables, metrics, and indicators are distinct but interconnected components in biodiversity monitoring and ecological assessment. Variables are the foundational, quantifiable data collected directly from monitoring or sampling, such as organism abundance, taxonomic composition, or environmental parameters like temperature or oxygen levels. From these variables, metrics represent specific aspects of ecosystem structure or function, such as species diversity or tolerance to pollutants. Metrics may take the form of simple indices or combine multiple variables to reveal ecological patterns or responses to stressors. Finally, indicators synthesize metrics and other data into tools that represent the overall state or quality of ecosystems. They help communicate results effectively to decision-makers and the public, supporting ecosystem management and conservation actions. The following principles and criteria can guide the selection of variables and metrics:

1. **Ecological Relevance and Parsimony**: Variables should represent key ecosystem attributes, such as taxonomic composition, abundance, and habitat characteristics. All essential variables must capture fundamental habitat

characteristics and reflect ecological quality or integrity. The required variables should be minimal, avoiding redundancy while ensuring comprehensive habitat condition assessment (the parsimony principle; Czúcz et al., 2021).

2. **Sensitivity**: Variables must respond to natural or human pressures that reduce favourable habitat condition (directionality principle; Maes et al., 2023).
3. **Contextual Relevance**: Variables should account for geographical, biogeographical, historical, and socio-economic factors influencing habitat conditions. Local environmental factors (e.g., temperature, topography, soil, and hydrology) are critical for setting thresholds and understanding habitat changes.
4. **Data Availability**: Historical data is essential for long-term trend analysis.
5. **Equivalence Across Member States**: After accounting for contextual factors, the habitat condition assessments should be comparable across EU Member States.
6. **Criteria for Variables**: Variables must meet the following requirements: intrinsic and instrumental relevance, validity, reliability, availability, simplicity, and compatibility (Czúcz et al., 2021). We can adjust the relevance and thresholds for the necessary variables based on habitat types and MS-specific conditions.
7. **Selection of Metrics**: A significant challenge in assessing biodiversity data is choosing the appropriate metric/indicator. Key criteria for metric selection include **Representativeness**: Metrics must reflect key aspects of biodiversity (e.g., species richness) or ecosystem health (e.g., tolerance to pollutants); **Calibration**: Metrics should be validated and calibrated for regional contexts and program goals; **Robustness**: Metrics must remain stable despite minor variations in sampling or data processing; **Interpretability**: Metrics should be understandable to both specialists and decision-makers.
8. Sampling plots can be adapted to the landscape's structure, either as transects (for elongated vegetation patches) or as quadrats. However, in general, the following plot sizes should be proposed according to these characteristics: 1) 25 m² (5 × 5 m) often used in dense shrublands (typically 1420, 1430, 1510, 1520); 2) 100 m² (10 × 10 m) is the standard size in studies of shrubland vegetation when characterizing the composition and structure of the plant community (typically 4020, 4030, 4040, 4050, 4060, 4090, 5110, 5120, 5130, 5330, 5410, 5420, 5430); 3) 400 m² (20 × 20 m) in shrub formations where individuals are of significant size (typically 5210, 5220, 5230, 5320).

A proposed list of **condition variables** for heath and scrub habitats is summarized in Table 4 and categorized as essential, recommended, or specific. **Essential** variables are key habitat characteristics that directly influence condition and are fundamental for effective monitoring and management. **Recommended** variables are common and relevant, but are optional and may be measured whenever possible to provide further insights into the habitat condition. **Specific variables** are specific to particular habitat types and should be measured in those habitats. This list is mainly based on the key characteristics of heath and scrub habitats as described in section 1.2.1 and on the MS methodologies for assessing the condition of these habitats. This categorisation reflects the ecological significance and practical applicability of each variable. Essential variables ensure the assessment of critical habitat features; recommended variables provide additional insights under appropriate conditions; and specific variables address particular habitat requirements, optimizing monitoring efforts. This structured framework ensures scientifically robust and context-specific habitat assessments.

Essential variables

The following **essential variables** are proposed for monitoring habitat condition under varying environmental and anthropogenic pressures. The most accessible metrics and methods are also specified below.

Physical variables

Soil water is critical for assessing habitat suitability, especially in ecosystems like heathlands and shrublands adapted to water scarcity or excessive moisture (e.g., some heaths). Shifts in precipitation patterns and declining groundwater levels pose a significant threat to the functionality and resilience of these ecosystems. Changes in soil moisture can disrupt key ecological processes, such as nutrient cycling, plant reproduction, and species interactions, leading to alterations in vegetation composition and reduced biodiversity.

For instance, in heathlands, which often thrive in moist but well-drained soils, even minor fluctuations in moisture can significantly affect the balance between dominant species and the overall habitat structure. NDWI (Normalized Difference Water Index) is a valuable remote sensing tool for monitoring these moisture dynamics over time, allowing early detection of stress conditions, tracking seasonal variation, and supporting conservation efforts by identifying areas at risk of degradation or requiring restoration.

Chemical variables

Soil pH is a chemical property influencing plant species distribution, nutrient availability, and overall ecosystem composition. Heathlands and scrubs, for example, thrive within specific pH ranges—acidic soils being essential for heathlands—making soil pH a key indicator of habitat condition and potential changes due to disturbances or environmental shifts. The pH scale, ranging from 1 to 14, is used to measure the acidity or alkalinity of soil. It is a logarithmic scale, where each unit represents a tenfold difference in acidity or alkalinity. These measurements help assess soil suitability for vegetation and nutrient cycling.

Monitoring soil pH is crucial for understanding soil chemical properties and ensuring the availability of nutrients required for healthy plant growth. A digital pH meter is the most accurate method to measure soil pH. This device uses a probe that can be inserted into a soil-water mixture or directly into the soil, depending on the type of meter, providing precise and reliable readings to guide land and habitat management decisions.

Soil fertility properties, including nutrient availability and productivity, can be evaluated using metrics like cation exchange capacity (CEC). This metric reflects the soil's ability to retain and exchange nutrients. Monitoring involves soil extraction techniques and atomic absorption spectrometry.

Organic matter content, measured as the percentage of organic matter or soil organic carbon (SOC), indicates soil fertility and vegetation support capacity. Organic matter decomposition is a key indicator of nutrient cycling, carbon sequestration, and soil fertility. Vegetation composition plays a crucial role in influencing decomposition rates, affecting microbial activity and overall soil health. A metric to assess this process is soil organic carbon (SOC, g/kg), which can help evaluate nutrient cycling, soil fertility, and carbon storage in habitats such as 4020*, 4050*, 5220* and 5230*.

Compositional variables

Characteristic species are key ecological indicators that reflect habitat quality and specific environmental conditions. These species play a vital role in defining the composition, structure, and functioning of ecosystems, offering valuable insights into the impacts of anthropogenic pressures and successional changes. Metrics for characteristic species typically include their presence, abundance, or dominance within a habitat. These metrics may focus on specific groups such as **dominant** species (those with the highest biomass or coverage) and **indicator** species (reflecting particular environmental conditions). Monitoring methods for characteristic species include field surveys, which involve direct observation and data collection on species composition.

The variety and balance of species within a habitat provide critical insights into ecological integrity. Changes in characteristics, species richness (the number of species), or abundance (the distribution of individuals among species) can signal habitat degradation or recovery, directly impacting ecosystem services such as pollination, nutrient cycling, and overall ecosystem function.

Metrics for assessing this variable include the **richness of characteristics plant species**, which quantifies the total number of plant species in a given area. These metrics help evaluate biodiversity levels and track ecosystem changes over time. Monitoring methods include field surveys, in which species are directly observed and recorded, and biodiversity plot assessments, which involve systematic sampling within defined areas to assess species composition and abundance.

Although some habitats have higher species richness than others (e.g., European Dry Heaths (4030), Alpine and Boreal Heaths (4060), Thermo-Mediterranean and pre-desert scrub (5330), West Mediterranean clifftop phryganas (5410)), optimal species diversity is a characteristic of each habitat, so these variables should be used to assess changes for the same habitat over time. **These metrics can also be applied to different taxonomic groups, particularly animals**. However, the essential thing will always be to measure plant diversity, as they form the basis of the food chain and the most visible structure of the habitat. However, measurements of birds, mammals, insects, or soil microorganisms can also serve as indicators of ecosystem functions such as dispersal, pollination, and nutrient cycling.

The presence of invasive non-native species is a key variable in compositional characteristics. Their proportion or density within a habitat helps assess the extent of invasion and its ecological impact. Monitoring methods include transect surveys and invasive species mapping, which effectively identify and quantify these species.

Invasion of *Agave sisalana* & *Agave fourcroydes* in 5220 of SE Iberian Peninsula
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Structural variables

Among **structural characteristics**, the ecosystem **vertical structure** refers to the layering of vegetation within a habitat, which determines its structural complexity and resource availability. A well-developed vertical structure enhances habitat quality by supporting diverse ecological interactions, providing nesting sites, foraging opportunities, and microclimatic buffering for species.

Heathland and shrubland habitats exhibit a wide diversity in their vertical structure, influenced by vegetation type, climatic and edaphic conditions, and natural or human disturbances. Some habitats, such as Dry Atlantic coastal heaths, feature a complex vertical structure, with taller shrubs like *Erica vagans* and *Ulex europaeus* growing on well-drained soils, providing greater vertical stratification and a more diverse habitat.

Also, in arborescent matorrals, such as those dominated by *Juniperus* spp. (5210) or *Ziziphus lotus* (5220), the vertical structure is higher and denser, with tree-like shrubs forming taller and more resilient formations. However, there are others dominated by low-growing vegetation and do not present a complex vertical stratification, such as Northern Atlantic wet heaths with *Erica tetralix* (4010), European Dry Heaths (4030), or Alpine and Boreal Heaths (4060). Metrics for assessing the vertical profile include the dominant shrub height, which reflects the habitat's structural maturity and complexity. This information helps evaluate the ecosystem's ability to support various species and ecological functions. Monitoring methods include field measurements, in which vegetation height is directly measured with tools such as measuring poles or clinometers.

Vegetation cover reflects the extent and density of plant growth within a habitat, providing critical insights into habitat quality, erosion risk, and the balance between early- and late-successional stages. Vegetation cover is particularly important for evaluating the impacts of management practices such as grazing or fire regimes on ecosystem health. Metrics for vegetation cover include the percentage or fractional vegetation cover, which quantifies the proportion of ground covered by vegetation. These metrics help identify trends in ecosystem stability and resilience over time.

Monitoring methods include ground-based vegetation cover surveys, in which field observations and measurements are made. However, for large habitat patches or extensive landscapes, remote sensing offers an efficient and scalable alternative, enabling the estimation of vegetation cover through spectral indices such as NDVI, derived from sensors like Sentinel-2 or Landsat. These data allow consistent monitoring over time and space, making them particularly suitable for assessing large or inaccessible areas.

Functional variables

Primary production is a key indicator of ecosystem functioning, representing the ecosystem's ability to capture energy through photosynthesis, sequester carbon, and support food webs. Variability in primary production provides valuable insights into changes in water or nutrient availability, often driven by climate change or land-use pressures. Metrics for assessing primary production include spectral vegetation indices, such as the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI). Often averaged annually, these indices quantify the amount of photosynthetically active vegetation and serve as proxies for ecosystem productivity. Monitoring methods rely on remote sensing, where vegetation indices are derived from satellite or aerial imagery. This approach allows for efficient, large-scale, and temporal tracking of primary production, providing essential data for understanding ecosystem dynamics and resilience.

Successional stage dynamics is vital for understanding how ecosystems evolve and how they respond to disturbances. Tracking these dynamics helps assess transitions between different successional stages, such as from shrubland to forest. Shrublands stabilize soil, enrich nutrient availability, and create microhabitats, thereby facilitating ecosystem development. Their transformation into forests depends on environmental conditions, disturbance regimes, and resource availability. Measuring successional stages can be done using the Vegetation Structural Complexity Index (ICE). This index can be calculated by multiplying each vegetation layer's coverage by its average height, yielding a quantitative measure of vertical stratification and successional progression in plant communities.

Another important variable for heaths and scrubs is the **fire regime** (fire frequency, intensity, and severity). Regular low-intensity fires prevent forest encroachment, promote biodiversity, and maintain habitat structure. Methods based on remote sensing (Differenced Normalized Burn Ratio, dNBR) enable tracking fire events and their impacts, supporting the development of fire management strategies.

Pollinator activity shapes the ecosystem structure, species distribution, and genetic diversity. A diverse and abundant pollinator community is crucial for enhancing cross-pollination, thereby increasing seed production and genetic diversity. Changes in pollination dynamics can indicate habitat degradation or shifts in species interactions and can be measured by estimating pollinator diversity and abundance. These measurements are critical when vegetation regeneration heavily depends on pollination, as they help evaluate the effectiveness of pollination services and their impact on ecosystem recovery (e.g., habitats 1520, 4030, 4090, 5110, 5220, 5330) (Kudrnovsky et al. 2020).

4090 Endemic Oro-Mediterranean Heaths with Gorse on Schists
© Javier Cabello

Landscape variables

Patch size (extent) is a critical landscape characteristic that influences habitat connectivity and population resilience. Larger patches generally support more stable and diverse ecosystems, while smaller, fragmented patches are more vulnerable to edge effects, invasive species, and biodiversity loss. Metrics for patch size include the average patch area, which provides insights into habitat distribution and landscape connectivity. Monitoring methods include GIS tools and habitat mapping, which allow for precise measurement and analysis of patch size and spatial patterns. These methods are essential for assessing habitat quality, identifying fragmentation, and guiding landscape-level conservation and management strategies.

Habitat connectivity evaluates the links between habitat patches and supports species movement and genetic flow. It can be assessed through landscape metrics and models that quantify both structural (based on the spatial arrangement of habitat) and functional (incorporating species-specific movement behavior) connectivity. Analytical approaches such as graph theory and circuit theory enable the simulation of potential dispersal pathways, the identification of critical corridors, and the detection of landscape barriers or bottlenecks. These tools support conservation planning by highlighting key areas for maintaining or enhancing connectivity and reducing habitat fragmentation.

Recommended variables

Below is a proposed set of variables to enhance habitat condition assessment. While these variables provide valuable insights, they can also increase the complexity of the analysis.

Physical variables

Soil structure and texture are defined by particle size distribution (sand, silt, and clay) and the stability of soil aggregates. These properties influence water retention, aeration, root penetration, and erosion resistance. Metrics such as mass of dry soil per unit volume (g/cm^3) can be assessed using soil core sampling, which provides precise soil monitoring and management data.

Chemical variables

Measuring **contaminants**, such as heavy metals (e.g., Pb, Cd, As), is crucial for assessing soil toxicity and understanding its impact on ecosystem health. These contaminants can disrupt microbial activity, harm plant and animal species, and reduce biodiversity. The concentration of heavy metals and pollutants (mg/kg) should be carefully monitored, particularly in areas under suspicion or with evidence of contamination.

Compositional variables

Harmful species, which often become dominant after disturbances or nutrient increases, can significantly alter ecosystems' composition, structure, and function. These species serve as indicators of habitat degradation, reflecting changes that may compromise ecosystem health. Monitoring their abundance or coverage (e.g., individuals/m^2) and presence/absence is recommended, especially following disturbances such as fires, overgrazing, or changes in habitat management. The presence of tall shrubs and trees can be used to assess the habitat's structural complexity and its potential to transition to a forest.

Functional variables

For functional variables, analysing **Plant functional types (PFTs) by growth form** provides valuable insights into how plant communities respond to disturbances and climate change. Together with other functional variables, these measurements help to understand the resilience and functioning of plant communities in changing environmental conditions.

Land Surface Phenology (LSP) monitors seasonal variations in vegetation cover using remote sensing (NDVI) to capture large-scale patterns of greening, senescence, and productivity. Changes in LSP can provide valuable insights into shifts in growing seasons, habitat quality, and ecosystem resilience, and are recommended for assessing climate change impacts and carbon dynamics. Key metrics to track LSP include the End of Season (EOS, date), Length of Season (LOS, days), Peak of Season (POS, date & NDVI value), Seasonal NDVI amplitude (unitless), and Greenness Integral (NDVI sum/average over time). These measures are derived from the same satellite imagery analysis and are recommended for assessing climate change impacts and the dynamics of carbon gains in ecosystems.

Landscape variables

Finally, landscape characteristics such as the fragmentation index and mosaic heterogeneity are recommended variables. The **fragmentation index** is a metric for evaluating landscape structure, as high fragmentation —characterized by small, isolated patches —can lead to reduced biodiversity, disrupted species movement, and decreased genetic diversity. An important indicator of fragmentation is the number of patches. This is recommended as a complementary metric to assess landscape structural complexity and connectivity, providing valuable insights into the impact of fragmentation on ecosystems.

The **spatial heterogeneity** of shrublands results from environmental variability, disturbances like fire or grazing, and human management practices. The key metric is the patch size Coefficient of Variation (CV) to measure this heterogeneity. These variables are recommended for evaluating diversity and spatial variation within scrub ecosystems, helping to understand the effects of disturbances and management practices on vegetation structure.

Specific variables

Specific variables are significant in particular habitats, such as arid and semi-arid areas, where environmental conditions are harsh. **Biological crusts**, composed of lichens, mosses, and cyanobacteria, are essential for soil stability, moisture retention, and nutrient cycling. They help prevent erosion and support plant regeneration, which is critical in maintaining ecosystem health. A simple metric for assessing biological crusts is percentage cover (%). This measurement is vital in environments where biological crusts significantly contribute to the resilience and sustainability of soil and plant communities, such as habitats 1520, 5330, and 5410.

Seed dispersal should be measured in habitats where regeneration depends on wildlife dispersal. Changes in dispersal patterns can also signal habitat degradation or shifts in species interactions. Key metrics for assessing seed dispersal include disperser diversity and abundance (species count, individuals/hour). These measurements are recommended when dispersal is critical for maintaining ecosystem structure, as they help understand the dynamics of species spread and ecosystem resilience, like in the habitats 5220 and 5230.

Similarly, **plant-plant facilitation**, primarily through nurse plants, plays a vital role in enhancing the survival of other species in harsh environments. Nurse plants provide shade, moisture retention, and protection from stressors, supporting biodiversity, stabilizing ecosystems, and influencing vegetation dynamics. It can be measured through assessing seedling survival under nurse plants versus open areas (%). This process is critical in specific settings, such as high mountains or arid ecosystems, where harsh environmental conditions challenge species' survival (habitats 4060, 4090, 5220, and 5330).

Alpine heaths.

Table 4. Variables, metrics and methods proposed to assess Heaths and Scrubs condition

Characteristics Variables	Importance	Metrics	Application	Measurement procedure	Monitoring periodicity and frequency (per 6-year cycle)
1. Abiotic characteristics					
1.1. Physical state characteristics					
Soil structure and texture	Soil texture, structure, and bulk density influence water and nutrient availability, soil stability, and resistance to erosion. Soil compaction reduces infiltration, aeration and root growth.	Mass of dry soil per unit volume (g/cm³).	Recommended	Bulk density: by drying a known soil volume at 105°C and dividing the dry mass by the soil's volume (g/cm³).	Every 6 years/ once
Soil water	While shrubs are adapted to water scarcity and excess, reduced rainfall or groundwater levels due to climate change or over-extraction threaten ecosystem functionality and resilience.	Spectral indices such as NDWI (Normalized Difference Water Index)	Essential	NDWI: from the difference between the near-infrared (NIR) and shortwave infrared (SWIR) reflectance.	Seasonally (Autumn, winter, spring, summer)/
1.1. Chemical state characteristics					
Soil pH	Crucial for nutrient availability, microbial activity, and plant growth in heathlands and shrublands. Species often thrive in acidic soils, and pH changes can disrupt ecosystem balance.	pH scale (1-14), acid-neutral-basic	Essential (Relevant in heaths such as 4030 and 4060, highly sensitive to pH variation. Also in areas under land-use pressure (e.g. fertilization, grazing, liming), or sites exposed to pollution or atmospheric deposition)	Soil pH meters, laboratory titration. Soil samples are typically collected at 0-10 cm, as this surface layer is critical for nutrient availability, microbial activity, and root interactions. For deeper assessments, sampling can extend to 20-30 cm.	Every 3 years/ twice
Fertility properties	Nutrient levels (nitrogen, phosphorus, potassium) directly affect plant health, productivity, and ecosystem balance.	Cation exchange capacity (CEC, cmol/kg).	Essential	CEC: with the ammonium acetate method at pH 7, where soil cations are exchanged with NH_4^+, then displaced and quantified to determine the soil's nutrient retention capacity.	Every 3 years/ twice

Characteristics Variable	Importance	Metrics	Application	Measurement procedure	Monitoring periodicity and frequency (per 6-year cycle)
1.2 Chemical state characteristics					
Organic matter content	A Key indicator of soil quality, ecosystem functionality, and carbon sequestration capacity, particularly in Mediterranean regions at risk of desertification. High organic matter content enhances fertility, moisture retention, and biological activity. Fluctuations in SOC can signal ecosystem changes.	Soil Organic Carbon (SOC) (% or g/kg)	Essential	SOC: Walkley-Black method (wet oxidation, % or g/kg) or dry combustion with a CHN analyzer (g/kg).	Every 3 years/ twice
Contaminants	Measuring contaminants, such as heavy metals (e.g., Pb, Cd, As), is essential for assessing soil toxicity and its impact on ecosystem health. Contaminants can disrupt microbial activity, harm plant and animal species, and reduce biodiversity.	Concentration of heavy metals, pollutants (mg/kg)	Recommended (Areas under suspicion or evidence of contamination)	Atomic Absorption Spectros-copy (AAS). Soil samples are digested with acids (e.g., nitric and hydrochloric acid) to extract metals, which are then quantified based on their specific absorption or mass-to-charge ratio.	Every 6 years/ once
2. Biotic characteristics					
2.1 Compositional state characteristics					
Characteristic plant species richness	High richness indicates resilient ecosystems, while low richness signals potential degradation. It helps prioritize conservation efforts, particularly for threatened species, which indicate habitat sensitivity to disturbances and degradation.	Species count	Essential	Record the number of species observed within a defined area (e.g., quadrats, transects, or plots) during field surveys, according to reference lists developed by habitat type and MS/region, including vascular plant species, bryophytes and lichen as relevant, depending on the habitat type.	Every 3 years/ twice
Indicator species	They signal habitat quality, and ecosystem engineers modify the environment to influence resource availability and biodiversity.	Species presence and abundance or coverage (1)	Essential	Record indicator species presence and abundance or coverage using quadrats or transects, estimating population density or percentage cover for each species.	Every 3 years/ twice

Characteristics Variable	Importance	Metrics	Application	Measurement procedure	Monitoring periodicity and frequency (per 6-year cycle)
2.1 Compositional state characteristics					
Animal species presence	Animal species play key functional or structural roles and indicate habitat quality (e.g. pollinators, herbivores, ground-nesting birds).	Species presence and number. Visual identification of species signs or traces that indicate their presence in the area	Essential	Record the number of species observed in a defined area (e.g., quadrats, transects, or plots) during field surveys, according to reference lists developed by habitat type and MS/region, including birds, invertebrates, reptiles, amphibians, and small mammals, as relevant.	Every 2-3 years
Invasive non-native species	Heathlands are highly vulnerable to invasions, while Mediterranean scrublands are relatively resistant, though disturbances like land-use changes, pollution, and climate change can facilitate invasions.	Record the presence of invasive species. Measure their abundance or coverage (1) by estimating population density (e.g., individuals/m²) or percentage cover.	Essential	Identify invasive species in the field using species checklists and record their presence or absence within defined plots or transects. Estimate their abundance by counting individuals or calculating the percentage covered within the survey area. Calculate the proportion of invasive species and total species richness within the habitat to determine invasion intensity.	Annually (for early detection) /6 times
Harmful native species	These species, often dominant after disturbances or nutrient increases, can alter composition, structure, and function, acting as indicators of habitat degradation.	Record the presence and abundance or coverage (1) of harmful species (e.g., individuals/m²)	Recommended (After disturbances - fires, overgrazing, or changes in habitat management)	To measure abundance or coverage, use quadrats or transects to count individuals per unit area (e.g., individuals/m²) or estimate the percentage of ground covered by the species. For presence, a survey will be conducted to define plots or transects and document whether harmful species are present.	Every 3 years/ twice
2.2 Structural state characteristics					
Dominant shrub cover and height	Shrub cover height reflects the effects of disturbances or land abandonment, influencing species composition and habitat functionality. It also determines microhabitat conditions.	Cover (%) Mean shrub height (m or cm)	Essential	Measure the cover and <u>height of dominant shrub</u> species (e.g., *Calluna vulgaris, Juniperus* spp.) at multiple points within a plot or along a transect, then calculate the average.	Every 3 years/ 2 times
Tall shrub and trees density	Their presence can indicate ecological transitions due to land abandonment or changes in fire and grazing regimes.	Tall shrub and tree density (individuals/m² or individuals/ha)	Recommended (Areas with the potential to transition to forest)	<u>Shrubs/Trees density</u>: count individuals within plots.	Every 3 years/ twice

Characteristics Variable	Importance	Metrics	Application	Measurement procedure	Monitoring periodicity and frequency (per 6-year cycle)
2.2 Structural state characteristics					
Vegetation cover	High cover provides erosion control, moisture retention, and habitat for wildlife, while low cover may indicate degradation or poor regeneration.	Percentage or fractional vegetation cover	Essential	Vegetation cover: quadrats or line-intercept transects, where the percentage of ground covered by vegetation is recorded. This field method provides fine-scale data and is suitable for small or heterogeneous patches. For large habitat patches, remote sensing by means of indices such as NDVI..	Field method: Every 3 years/ twice Remote sensing: Every year / 6 times.
Biological crust cover	Essential for soil stability, moisture retention, and nutrient cycling, biocrusts (lichens, mosses, cyanobacteria) prevent erosion and support plant regeneration.	Percentage cover (%)	Specific (habitats of arid and semiarid areas, 1430, 1520, 5220, 5330)	Biocrust cover: quadrats	Every 3 years/ twice
2.3 Functional state characteristics					
Primary production	Aboveground Net Primary Productivity (ANPP) dynamics reflects vegetation changes, water availability, and nutrient cycling. In arid and semi-arid environments, it is highly sensitive to drought and rainfall patterns.	Normalized Difference Vegetation Index (NDVI)	Essential	NDVI: from satellite or drone imagery to estimate vegetation productivity.	Annually (continuous time series)/6 times
Plant functional types	Growth form helps assess plant functional types (PFTs) in terms of growth, resource use, and ecological adaptation.	Growth form classification	Recommended (Habitats affected by wildfires, over-grazing, climate change, and eutrophication)	Plants are classified into growth form categories based on their structure: herbs, shrubs, vines/lianas, grasses/sedges, and rosettes; the use of standardized databases (e.g., TRY, LEDA) ensures consistency in classification.	Every 3 years/ twice
Pollinator activity	A diverse and abundant pollinator community enhances cross-pollination, increasing seed production and genetic diversity. Changes in pollination dynamics can indicate habitat degradation or shifts in species interactions.	Pollinator diversity and abundance	Essential (Critical when vegetation regeneration heavily depends on pollination: 1520, 4030, 4090, 5110, 5210, 5220, 5330)	Pollination diversity: observing and counting pollinators, recording visitation rates per flower or plant over set time intervals.	Every 3 years/ twice

Characteristics Variable	Importance	Metrics	Application	Measurement procedure	Monitoring periodicity and frequency (per 6-year cycle)
2.3 Functional state characteristics					
Land Surface Phenology (LSP)	LSP tracks seasonal variations in vegetation cover using remote sensing (NDVI) to capture large-scale patterns of greening, senescence, and productivity. Changes in LSP can indicate shifts in growing seasons, habitat quality, and ecosystem resilience.	End of Season (EOS, date), Length of Season (LOS, days), Peak of Season (POS, date & NDVI value), Seasonal NDVI amplitude (unitless), Greenness Integral (NDVI sum/ average over time)	Recommended (For assessing climate change impact and carbon gains dynamics)	LSP: satellite-derived vegetation indices such as NDVI (from sensors like MODIS, Sentinel-2, or Landsat). Time-series analysis identifies key phenological metrics — Start of Season (SOS), End of Season (EOS), and Peak of Season (POS) — based on changes in greenness.	Annually (continuous time series)/
Seed dispersal	Dispersal by animals, wind, or water influences species distribution, genetic diversity, and community structure. Changes in dispersal patterns can indicate habitat degradation or shifts in species interactions.	Dispersers abundance (species count, individuals/hour).	Specific (When dispersal by animals is a critical factor for ecosystem structure, habitats 5220 & 5230)	Disperser diversity and abundance: direct observations or camera traps, identifying species involved in seed movement.	Every 3 years/ twice
Plant-plant facilitation	Nurse plants provide shade, moisture retention, and protection from stressors, enhancing the survival of other species in harsh environments. This process supports biodiversity, stabilizes ecosystems, and influences vegetation dynamics.	Seedling survival under nurse plants vs. open areas (%)	Specific (Harsh environments such as high mountains or arid ecosystems, i.e., 4060, 4090, 5120, 5220, 5330)	Seedling survival: compare survival rates of seedlings under nurse plants versus open areas.	Every 3 years/ twice
Successional stage	Shrublands stabilize soil, enrich nutrient availability, and create microhabitats, thereby facilitating ecosystem development. Their transformation into forests depends on environmental conditions, disturbance regimes, and resource availability.	Vegetation Structural Complexity Index (ICE) is based on the combination of coverage (%) and height (m) of the different vegetation layers.	Essential	ICE can be calculated by multiplying the coverage of each vegetation layer by its average height, providing a quantitative measure of vertical stratification and successional progression in plant communities.	Every 3 years/ twice
Fire regime	Regular low-intensity fires are essential for preventing forest encroachment, promoting biodiversity, and maintaining habitat structure.	Burn severity	Essential	Burn severity can be assessed by calculating the Differenced Normalized Burn Ratio (dNBR), which quantifies vegetation and soil changes caused by fire	Post-fire event (ideally within the same season)/ As needed (following each relevant fire)

Characteristics Variable	Importance	Metrics	Application	Measurement procedure	Monitoring periodicity and frequency (per 6-year cycle)
3. Landscape					
Patch size (extent)	Larger patches typically support more diverse species and more complex ecological processes, while smaller patches may be more vulnerable to fragmentation, biodiversity loss, and environmental stress.	Mean patch size (hectares or m²)	Essential	<u>Mean patch size</u>: calculate the average area of all patches within the landscape.	Every 6 years/ once
Fragmentation index	High fragmentation, characterized by small, isolated patches, can reduce biodiversity, disrupt species movement, and decrease genetic diversity.	Number of patches	Essential (complementary to landscape structural complexity and connectivity)	<u>Number of patches</u>: GIS tools or satellite imagery to count the distinct habitat patches in a defined landscape area.	Every 6 years/ once
Habitat connectivity	High connectivity facilitates the migration and survival of species, reduces the risks of inbreeding, and enhances the ability of ecosystems to recover from disturbances	Landscape connectivity (permeability)	Recommended	Landscape permeability: analyze landscape features using least-cost path analysis or graph theory, assessing how easily species can move between patches based on factors like terrain, roads, and water bodies.	Every 6 years/ once
Mosaic heterogeneity	Scrubs often exhibit a heterogeneous distribution of vegetation due to environmental variability, disturbances (such as fire or grazing), and human management practices.	Coefficient of Variation (CV) of patch sizes	Recommended	<u>Coefficient of Variation (CV) of patch sizes</u>: calculate the standard deviation of patch sizes and divide it by the mean patch size. Both metrics are typically derived from spatial analysis in GIS.	Every 6 years/ once

(1) When species are measured in terms of cover or area, they can be considered structural variables, as they reflect habitat structure and dominance patterns rather than mere composition.

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 each variable's condition. 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 within a given ecosystem type and across different ecosystem types for the same variable. This ensures that derived indicators are compatible and comparable, and that their aggregation is ecologically meaningful (UN, 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. In contrast, the lowest value may represent a degraded state in which ecosystem processes fall below the threshold required to maintain function (Keith et al., 2013; UN, 2021). For example, pH values in freshwater ecosystems clearly indicate whether biological life can be sustained. At the same time, 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.

It is essential to consult technical documents and local legislation for detailed thresholds and specific contexts. These values for habitats must conform to ecological and precautionary principles to ensure their long-term viability. This process requires integrating the best available scientific knowledge and assuming environmental variability. Ideally, reference values should be based on empirical data from relevant reference systems or historical reference periods. In real life, such baseline data are, however, scarce, incomplete, or lacking.

These guidelines do not aim to prescribe specific threshold values. Instead, they outline the main approaches and procedures 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.

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 a historical period (e.g., pre-industrial) as a reference state, as proposed by Stoddard et al. (2006) and Keith et al. (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 helpful for trend analyses. Likewise, where historical pristine conditions are clearly documented, they may serve as valid reference states under the undisturbed comparison approach.

Approaches for Establishing Reference Values

Absolute biophysical boundaries

This method establishes reference values by identifying situations in which observed values of variables exceed certain limits that define the habitat, e.g. 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) 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. The method is also easy to apply, with clear, quantifiable indicators.
Disadvantages: It applies to a limited number of variables, typically those with direct negative impacts on habitat condition.

Comparison to empirical cases considered to be in good condition – Reference areas, reference communities

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.

However, this method also has several limitations, as defining areas with optimal conditions can be difficult, particularly in habitats shaped by traditional management practices, such as heathlands, which are often the result of historical grazing or burning. In habitats such as heathland and scrub, which represent different successional stages and may be subject to disturbance (e.g., fire or grazing), establishing intact states in practice is difficult. In addition, differences in successional stage or disturbance history complicate standardisation across intact sites. The availability and documentation of high-quality reference areas may also be limited, making them difficult to identify and use in some regions. One way to overcome this difficulty is to base area selection on expert knowledge, as proposed for habitat 5120 in southern Spain (Requena-Mullor et al., 2018b).

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 from the difficulty of identifying sufficient numbers of suitable reference sites in historically altered environments.

Comparison to cases with a natural disturbance regime

This approach is closely related to the previous one, assuming 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 primaeval 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 challenging to identify unaltered or naturally disturbed habitats for certain types (Keith et al., 2020). Additionally, defining the undisturbed state based on a relatively short period may overlook disturbance legacies that persist over longer timescales (Alfaro-Sánchez et al., 2019).

Advantages: This approach provides transparent, empirically grounded criteria for defining reference conditions and can benefit from large-scale data 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 some instances of good condition correlate with specific levels of a condition variable. The advantage of modelling is that it allows inference of reference values when empirical examples of good or undisturbed conditions 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). 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).

Models based on ecosystem dynamics aim to predict and explain the trajectories of ecosystems by reproducing their internal and external interactions (Cosme et al., 2022). These models simulate ecological processes, such as vegetation growth, succession and natural disturbance regimes, to estimate baseline values of habitat conditions. These models often rely on historical data or minimally disturbed sites to predict the state of ecosystems under limited human influence. One of their main advantages is their simulation capability, which provides insight into predicted ecosystem conditions when direct data are unavailable. These models offer high predictive power, particularly for understanding long-term ecological trends and ecosystem responses to disturbances or management interventions. However, they require accurate input data based on sound ecosystem-process assumptions.

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 the 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. The complexity of the models can also pose problems, as validation of their results often requires extensive field data.

Despite these difficulties, this method can be particularly valuable for ecosystems such as shrublands, where natural or anthropogenic disturbances, such as fire cycles, play a crucial role in shaping them.

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 conditions 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 value (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 condition of habitats across the entire assessed territory. In other words, this approach is not based directly on reference situations in good condition, but rather 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: This method requires appropriate, quantitative datasets representing the reference state. 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 reference values and thresholds based on expert judgement is a common practice, notably where other sources of information are lacking – for instance, in 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 complement 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 particular 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. The scarcity of suitable experts for particular habitats and Member States may also constrain its use.

Table 5 provides an overview of the approaches used to establish thresholds and reference values for the proposed harmonized condition variables, drawn from methodologies applied by Member States (MSs) and documented in the literature.

Given the uncertainties involved in setting reference levels, a combination of approaches is generally recommended to improve reliability. The methods 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 whether the variables used indicate good or poor 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 each variable's characteristics. 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 and not good; or good, medium and 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.

In habitat condition assessments, each characteristic and its associated variable are likely to be measured in different units. Owing to the various metrics and magnitudes used to characterise habitats, the values obtained from their measurements require some form of standardisation – e.g., rescaling – to build indicators that combine multiple variables. These values are normalised using reference levels and reference conditions, allowing comparison across variables. Measurement values are thus scaled relative to their reference levels, thereby normalised to a common scale and aligned in the direction of change. They can then be combined to form a composite index or used to obtain an overall condition result through appropriate aggregation approaches (see further details in Section 3.3 on Aggregation).

Thresholds, limits, and reference values must be tested against sufficiently broad data sets that cover the full range of habitat conditions—from degraded to high-quality examples.

Table 5. Overview of approaches used to establish thresholds and reference values for determining favourable condition, applicable to the proposed variables for assessing the condition of the heath and scrubs habitats

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

Characteristics Variables	Biophysical boundaries	Comparison to good condition cases	Comparison to undisturbed	Modelling variables	Statistical assessment	Expert judgement	Application
1. Abiotic characteristics							
1.1 Physical characteristics							
Soil structure and texture							Recommended
Soil water							Essential
1.2 Chemical characteristics							
Soil pH							Recommended
Fertility properties							Essential
Organic matter content							Essential
Contaminants							Recommended
2. Biotic characteristics							
2.1 Compositional state characteristics							
Characteristic plant species richness							Essential
Indicator species							Essential
Animal species							Essential
Invasive non-native species							Essential
Harmful native species							Recommended

Characteristics Variables	Biophysical boundaries	Comparison to good condition cases	Comparison to undisturbed	Modelling variables	Statistical assessment	Expert judgement	Application
2. Biotic characteristics							
2.1 Structural state characteristics							
Dominant shrub cover and height							Essential
Tall shrub and trees density							Recommended
Vegetation cover							Essential
Biological crust cover							Specific
2.3 Functional state characteristics							
Primary production							Essential
Plant functional types							Recommended
Land Surface Phenology (LSP)							
Pollinator activity							Recommended
Seed dispersal							Recommended
Plant-plant facilitation							Specific
Successional stage							Specific
Fire regime							Essential

Characteristics Variables	Biophysical boundaries	Comparison to good condition cases	Comparison to undisturbed	Modelling variables	Statistical assessment	Expert judgement	Application
3. Landscape							
Patch size (extent)							Essential
Fragmentation index							Essential
Habitat connectivity							Recommended
Mosaic heterogeneity							Recommended

(1) When species are measured in terms of cover or area, they can be considered structural variables, as they reflect habitat structure and dominance patterns rather than mere composition.

3.3 Guidelines for the aggregation of variables at the local level

Ecological assessments require integrating 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 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 are the key information needed for evaluating the conservation status of structure and functions at the biogeographical level.

3.3.1 Overview of aggregation methods

Based on the literature (e.g., Langhans et al., 2014; Borja et al., 2014), two main aggregation approaches can be distinguished: the one-out, all-out rule (minimum aggregation) and additive aggregation (e.g., 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 minimum aggregation, the aggregated value is the minimum of the measured variable values.

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 actual overall status.

A precautionary OOAO approach is also used when aggregating parameters to assess conservation status under the Habitats Directive, 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 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*) for each variable.

Averaging approaches are among the most 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 a 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 variable values (rescaling)

In assessing habitat condition~~,~~ each characteristic and associated variable is likely to use 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 a common scale, allowing aggregation into condition indices that reflect overall condition at a given plot or location.

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

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

Where:

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

Source: Vallecillo et al, 2022

3.3.2 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 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). Thus, each variable's value will be in the range 0 to 1.

Step 2 – Aggregation of normalised variables

The aggregation of the normalised values of the variables in then carried out. 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, 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, and v_i is the rescaled value of the corresponding variable (between 0 and 1). As a result, 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:

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

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 the aggregation at the biogeographical region scale

Following the Article 17 guidelines, each monitoring station must be classified as either in 'good condition' or 'not in good condition' based on aggregating the variables used to assess the habitat structure and function at this local scale. The next step at **the biogeographical region level** is to calculate the proportion of habitat in 'good condition'. If 90% or more of the habitat area is in good condition, the structure and functions parameter is classified as 'favourable'; If more than 25% is not in good condition, it is classified as 'unfavourable-bad'. Results between these thresholds (90%-75% in good condition) are classified as 'unfavourable-inadequate.' This rule highlights the importance of using a sample design that ensures a statistically sufficient representation of the total habitat area and diversity. However, MS may choose to adopt stricter thresholds, particularly for endangered habitats or those with a very limited distribution, which may require that their entire area be in good condition.

Addressing **spatial heterogeneity** within large or ecologically diverse regions can further improve assessments. This can be achieved by evaluating habitat conditions within sub-regions (e.g., ecozones or management units) to capture spatial variation accurately. This will enable more nuanced assessment and better prioritization of conservation efforts. This methodology provides a consistent yet flexible framework for scaling up local assessments to the biogeographical region, ensuring compliance with Article 17 requirements and supporting more detailed conservation insights.

3.5 Guidelines on general sampling methods and protocols

Harmonized monitoring protocols are essential for assessing the health, biodiversity, and ecological integrity of European heaths and scrubs. These protocols must provide standardized methods for collecting, analysing, and interpreting data, ensuring consistency and comparability over time and across different regions. Some recommendations on sampling designs and monitoring protocols are exposed:

Site and Plot Selection: Monitoring will be conducted at representative sites within each targeted habitat. Each site will consist of at least three permanent plots, though additional plots may be established in habitats with high heterogeneity to capture vegetation variability adequately. The recommended plot size for heath and scrub habitats is 16-25 m² (Candullo et al., 2024), typically in a square configuration. Subplots for sampling the herbaceous and biocrust layers, where applicable, will be distributed randomly within plots in a stratified manner to ensure adequate coverage of the vegetation.

Permanent plots: Establishing permanent plots requires durable markers, such as aluminium stakes or similar materials, to mark the corners. These plots will be georeferenced using GPS and documented with photographs to facilitate relocation and provide visual records of baseline conditions. Markers should be positioned to minimize disturbance to the vegetation while ensuring long-term durability.

Data collection:

- To sample the physical and chemical characteristics of soil, at least 2-3 soil sampling points per plot, increasing the number in heterogeneous soils or habitats with higher variability.
- The vegetation will be stratified into functional layers for detailed observations. The key layers include a) the shrub layer, consisting of shrubs or trees between 0.3 and 5 meters in height; b) the herbaceous and moss layer, including soil-dwelling vascular plants, bryophytes, and lichens; and c) the invasive or harmful species must also be identified. Non-vascular species, such as fungi and algae, are excluded. Observations will focus on live vegetation, with any necessary identifications conducted outside the sampled area to prevent disturbance.
- The primary parameters to be measured include species abundance and coverage, the percentage of ground area occupied by each species, measured visually or using a mesh frame for precise estimates. All data will be recorded according to standardized taxonomic protocols to ensure comparability across sites and over time.
- Monitoring vegetation structure should include key parameters that reflect its vertical and horizontal organisation. To measure vertical structure, we can measure the

maximum vegetation height at different points within the plot. To characterize the horizontal organization, we must estimate the percentage cover of each structural layer (shrubs, herbaceous plants, mosses, and lichens).

- To sample soil biological activity, which reflects processes such as organic matter decomposition and nutrient cycling, we can then follow these points:
  - Sampling points should be stratified within the plots (e.g., 3-5 points per plot). We should collect samples from the surface layer (0-10 cm) and the subsoil layer (10-30 cm) to capture biological activity across different soil horizons. Cylindrical augers can be used to extract samples without compacting them. Subsamples from within a plot can be mixed to obtain a representative sample.
  - The key biological parameters to measure must include soil respiration, microbial biomass, and diversity.

Monitoring frequency: It is recommended that observations be conducted every 3 years to balance resource availability and data quality, especially during periods of rapid environmental change or in habitats of high conservation value. Monitoring vegetation should occur when most species are fully developed to maximise sampling accuracy.

Quality Assurance and Observer Calibration: Field teams should undergo training and calibration exercises to ensure consistency in data collection. At least 10% of subplots will be re-sampled to assess observer error, and independent validation surveys should be conducted on 5-10% of subplots to ensure data reliability. The use of photographic records and standard reference materials will further enhance consistency.

Remote sensing monitoring: NDVI (a surrogate for primary production) can be monitored by drones, and Sentinel-2 images can be effectively integrated with vegetation sampling in 16-25 m² plots, leveraging remote sensing capabilities to scale point observations to broader landscapes. This integration ensures a robust connection between field-based vegetation sampling and remote sensing data, enabling comprehensive monitoring of vegetation dynamics at local and landscape scales. The following proposal outlines this approach:

1. Precise Georeferencing of Plots: Ensure that the 16-25 m² vegetation plots can be accurately located within satellite images using GPS (sub-meter accuracy, if possible) to georeference each plot. Record the coordinates of the plot vertices and, if necessary, mark the center for cross-referencing. Capture aerial photographs with drones or cameras to verify the exact location within the landscape.
2. Integration of Sentinel Data with Plot Sampling: Use Sentinel-2 images with 10 m spatial resolution for visible and near-infrared (NIR) bands, which are ideal for calculating NDVI. For calibration purposes, we can download images corresponding to the field sampling dates to ensure temporal comparability. To estimate the annual dynamics and seasonality of the canopy, we process the image time series we focus on.
3. Calibration of NDVI with Field Data: We can validate and improve the interpretation of NDVI values derived from Sentinel images using direct data from the plots. Dry biomass can be measured in 1 m² subplots within the larger plots (avoiding significant impacts on long-term sampling). Correlate these measurements with Sentinel-derived NDVI values to establish quantitative relationships.

Expected Outcomes: The proposed monitoring framework will provide robust, high-quality datasets to track compositional, structural, and functional trends in heath and scrub habitats. Taxonomic harmonization will be achieved using R packages such as bdc, taxadb, taxize, or LCVP. Metadata will adhere to the Darwin Core schema, including detailed documentation of methodologies, taxonomic references, and observer details. Specimens will only be collected for necessary identification and should come from areas outside the plots. Visual coverage estimates will use standardized methods, but ordinal scales (e.g., Braun-Blanquet or Domin scales) may be employed if converted to percentage cover for analysis. These data will enhance understanding of habitat dynamics in response to climate change and other pressures, informing conservation and management strategies locally and in Europe. By integrating new and existing datasets, this program will facilitate cross-site comparisons and contribute to long-term ecological research networks, such as eLTER, fostering harmonized habitat monitoring and protection approaches.

3.6 Criteria to select a minimum number of localities

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 sampling localities 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 and 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 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 whole 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 to capture the full range of habitat condition across its distribution. This includes both well-conserved areas with minimal human impact and areas affected by degradation and subject to different pressures. To reflect the diversity of pressures acting on the habitat, localities should span a range of intensity levels – from low to high – and account for different sources of disturbance, such as urbanisation, agriculture, and climate change.

Presence inside and outside Natura 2000 sites: The assessment and monitoring of habitat conservation status must be carried out both inside and outside Natura 2000 sites. This requires selecting localities – and an appropriate number of plots – that reflect the proportion to the habitat’s distribution within and outside the Natura 2000 network.

Habitat fragmentation at the 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 helps build 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: Leveraging existing monitoring sites with historical data can strengthen 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.

Given the heterogeneity of habitat types, it is highly recommended to consult a sampling statistician when determining the sample size— the minimum number of plots required to ensure representativeness 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 and plots should be sufficient to yield a statistically robust sample size. This ensures that the collected data can be generalised to the entire habitat type within the region.
- Statistical methods, such as stratified random sampling, are often used to ensure that all habitat subtypes and environmental gradients are adequately represented.

Sampling design:

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

Replication and randomisation:

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

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

Several new technologies, including scrubs and heaths, are becoming increasingly popular for monitoring vegetation. Here are some innovative technologies that can be used to monitor the condition of these ecosystems:

Remote sensing technologies, such as satellite imagery and unmanned aerial drones, have revolutionized how we monitor vegetation cover, health, and changes over time, particularly in ecosystems such as scrubs and heaths. Satellite imagery provides a broad perspective, mapping large areas and tracking changes in vegetation patterns. Aerial drones offer a more detailed view, capturing high-resolution images that can highlight specific areas of interest within scrublands and heathlands. LiDAR technology complements these remote sensing techniques by providing precise 3D models of vegetation structure and topography. By emitting laser pulses and measuring the reflected light, LiDAR can create detailed maps that reveal the vertical structure of scrublands and heathlands. This information is crucial for assessing habitat complexity, identifying vegetation layers, and understanding the distribution of plant species within these ecosystems. In addition, hyperspectral imaging provides detailed information about the vegetation's spectral signature. This advanced technology enables precise identification of plant species, assessment of vegetation stress levels, and overall evaluation of ecosystem health. By analyzing the unique spectral characteristics of scrubs and heaths, hyperspectral imaging can offer insights into the condition of these habitats, helping researchers and land managers make informed decisions about conservation and management strategies.

Monitoring heathland and scrub vegetation is crucial for effective conservation management. Recent advancements in remote sensing and other technologies have provided new methods to enhance the accuracy and efficiency of vegetation monitoring.

Table 6. Modern approaches for monitoring heath and scrub habitats based on recent research

Title	Method	Application	Benefits	Citation
Photogrammetric Point Clouds from UAVs	High-resolution surface models from photogrammetric point clouds using UAVs	High-resolution surface models from photogrammetric point clouds using UAVs	Allows for the isolation of vegetation types based on height, informing habitat management strategies	Vafidis et al. 2021
Integration of Site-Based and Remote Sensing Methods	Combining remote sensing methods with traditional site-based assessments.	Monitoring compositional, structural, and functional attributes of vegetation.	Offers broad-scale, automated, and repeatable monitoring, improving ecological assessments across scales.	Lawley et al. 2016
Hyperspectral Mixture Analysis and Decision Tree Classifiers	Decision tree modeling of subpixel fraction estimates using hyperspectral remote sensing images.	Assessing the conservation status of heathland by identifying heather age structure.	Provides detailed structural and functional characteristics necessary for effective conservation management	Delalieux et al. 2012

Title	Method	Application	Benefits	Citation
UAV-Based Gap Mapping	UAV-mounted cameras to classify gaps in vegetation.	Monitoring gap areas in Florida rosemary scrub are crucial for endemic and endangered species.	Enhances traditional field methods, enabling better exploration of spatial dynamics and conservation management.	Charton et al. 2021
Rapid Field Assessment and Remote Sensing Citation	Combining aerial imagery analysis with rapid field surveys.	Comparing the effectiveness of different scrub management strategies.	Allows for rapid data collection over large areas, providing insights into scrub encroachment and grassland quality	Redhead et al. 2012
Stereo Aerial Photography for Vegetation Heights	High-resolution stereo aerial photography to estimate vegetation heights.	Monitoring rangeland health, post-fire recovery, and wildlife habitat	Provides a cost-effective alternative to LiDAR, suitable for broad-scale monitoring	Gillan et al. 2014
Airborne Imaging Spectroscopy	Hierarchical land/vegetation type classification using airborne imaging spectroscopy	Detailed mapping and assessment of NATURA 2000 heathland habitats.	Offers high accuracy in habitat characterization, aligning with field-based workflows	Haest et al. 2017
Ecosystem functioning characterization through spectral vegetation indices	Parameterization of the annual dynamics of spectral vegetation indices (NDVI, EVI) to obtain functional attributes of the vegetation canopy.	Assessment of changes in ecosystem functioning and their relationship to environmental controls	It provides a functional view of habitats based on annual and seasonal changes in primary productivity.	Alcaraz et al. 2009, Cabello et al. 2009, Cabello et al. 2012a, 2012b
LiDAR and Aerial Photography for Footpath Erosion	Combining LiDAR and aerial photography with on-site measurements.	Monitoring footpath erosion and its impact on heathland environments	Provides comprehensive assessments of soil loss, vegetation damage, and hydrology, aiding in land management	Rodway-Dyer & Ellis 2018

The application of **eDNA technology** offers a cutting-edge approach to monitoring biodiversity, ecosystem health, and species dynamics in scrubs and heaths, providing valuable information for conservation and management purposes. eDNA analysis can provide insights into the biodiversity of scrublands and heathlands by detecting species using genetic markers. This non-invasive technique enables researchers to comprehensively survey the plant, animal, and microbial diversity of these ecosystems. By using eDNA, we can also detect invasive plant species and provide information on the overall health and functioning of scrublands and heathlands. Changes in the eDNA signals can indicate disturbances, pollution, or other stressors affecting the ecosystem, enabling early detection and intervention.

Other technologies:

Internet of Things (IoT) Sensors: Field-deployed IoT sensors can gather real-time data on environmental variables, such as temperature, humidity, and soil moisture. This data can help assess the environmental conditions affecting scrublands and heathlands and inform management decisions.

Mobile Apps and Citizen Science: Mobile applications and citizen science platforms enable community members and volunteers to collect data. These tools can gather information on species occurrence, habitat quality, and disturbances in scrub and heath ecosystems.

International programs and open data sources that provide valuable information about these habitats:

European Environment Agency (EEA): The EEA provides various environmental data, including information on European habitats and vegetation. They offer reports, datasets, and interactive tools for studying vegetation types such as scrubs and heaths.

European Vegetation Archive (EVA) (Chytrý et al. 2016, https://euroveg.org/eva-database/): EVA is a database that compiles vegetation data from across Europe. It includes information on plant communities, habitats, and vegetation classifications, making it a valuable resource for those interested in studying vegetation in the region. It is an initiative of the European Vegetation Survey Working Group aimed at establishing and maintenance of a single data repository of vegetation-plot observations (i.e., records of plant taxon co-occurrence at particular sites, also called phytosociological relevés) from Europe and adjacent areas and to facilitate the use of these data for non-commercial purposes, mainly academic research and applications in nature conservation and ecological restoration. The initiative follows the EVA Data Property and Governance Rules. EVA also includes ReSurveyEurope, a European database of repeated records from the same plots. EVA closely cooperates with the Global Index of Vegetation-Plot Databases (GIVD), the Global Vegetation Database (sPlot), the Plant Trait Database (TRY) and the Euro+Med PlantBase (Euro+Med).

European Topic Centre Biodiversity and Ecosystems (ETC BE) [2]: supports the European Environment Agency in biodiversity-related activities. It may provide access to data and reports on vegetation types, including scrubs and heaths, across Europe. It contributes to integrated systemic assessments of terrestrial, freshwater and marine ecosystems. It supports the implementation of the European Biodiversity Data Centre and the Biodiversity Information System for Europe (BISE) by the European Environment Agency. This includes explicitly data collected under the Birds and Habitats Directives and from the development of biodiversity indicators, with special emphasis on the spatial dimension of data.

International Union for Conservation of Nature (IUCN): The IUCN offers programs and publications on conservation efforts across various habitats, including scrubs and heaths.

Global Biodiversity Information Facility (GBIF): GBIF provides a free, open-access data platform that enables users to discover, access, and use biodiversity data from around the world, including data on scrubland and heathland species.

Integrated Biodiversity Assessment Tool (IBAT) (https://ibat-alliance.org/): IBAT provides access to critical and significant biodiversity data and enables users to access key datasets to support decision-making and conservation efforts. IBAT integrates biodiversity data from leading organizations like the International Union for Conservation of Nature (IUCN), BirdLife International, and the World Database on Protected Areas (WDPA). This ensures the data available through IBAT is reliable and up to date. IBAT is freely accessible online, making it a valuable resource for researchers, policymakers, conservationists, and anyone interested in biodiversity conservation. The user-friendly tool supports efforts to mainstream biodiversity considerations into decision-making processes.

[2] https://www.eionet.europa.eu/etcs/etc-be

4. Guidelines to assess fragmentation at appropriate scales

Circuit theory can be applied to generate omnidirectional connectivity maps that identify movement paths and barriers across extensive areas (Pelletier et al., 2014). This method is beneficial for identifying natural corridors that require protection or restoration, detecting the most fragile or critical points in the connectivity network, and planning effective conservation strategies to maintain or improve habitat connectivity. Graph theory and percolation analysis enable quantification of habitat connectivity at multiple scales, revealing scale-dependent sensitivity and critical "keystone" patches (Keitt et al., 1995). By representing the habitat mosaic as a mathematical "graph", this method uses the percolation theory to quantify connectivity at multiple scales from empirical landscape data. Results obtained by

Different methods exist for assessing fragmentation at the local scale. For example, the method proposed by Moreno-de las Heras et al. (2011) integrates remote sensing, spatial analysis, and landscape ecology tools to assess shrubland fragmentation. Focusing on the size and distribution of vegetation patches provides a clear and quantitative way to evaluate ecosystem health and supports informed decision-making for conservation and restoration efforts. This method analyzes the distribution of vegetation patch sizes to measure and assess fragmentation in shrublands. The approach focuses on detecting changes in vegetation patterns, which serve as key indicators of ecosystem health.

Key steps include identifying areas with different levels of fragmentation — reference zones (undisturbed) and disturbance zones (e.g., affected by grazing or fires) — and patch-size analysis using mathematical tools to describe how patch sizes are distributed across the landscape. Finally, landscape-scale fragmentation is estimated by comparing patch-size distributions between undisturbed and disturbed areas. Identify changes in the overall distribution pattern, such as a shift from a power-law to a truncated or exponential form, which indicate fragmentation.

Please also see the Technical Guidelines for assessing habitat type fragmentation (a separate volume in this collection of technical guidelines).

Mountain *Cytisus purgans* formations (5120). © Daniel Goñi

5. Next steps to address future needs

These guidelines propose moving towards harmonized procedures for the assessment and monitoring of heath and shrub habitats, based on existing methodologies and promoting common approaches that yield comparable results. To ensure that habitat condition assessments are comparable across countries, it is essential to define a 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 "heath and scrub" 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.

Possible next steps to continue progressing in this direction could include the following activities:

Promoting harmonisation of methodologies in all EU MS

- **Agree on a common set of variables and test the proposed 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 helpful to identify gaps of knowledge, flaws of applicability and robustness and reliability of results. The evaluation should provide recommendations for further integration into the harmonized procedure.
- **Develop further, test, and standardise methods for establishing reference values and thresholds to determine good condition,** for aggregating results from all variables measured at the local scale and for each biogeographical region.
- **Develop further and test the criteria for selecting monitoring localities and the sampling design** to ensure a sufficiently representative sample that allows for proper 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 and reflect 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 the overall condition assessment for each habitat.
- **Promote harmonised remote sensing approaches to assess ecosystem functioning**: Remote sensing indicators can effectively capture how ecosystem functioning responds to global change drivers. However, to ensure their ecological relevance and comparability across regions, these indicators must be validated with field data for each habitat type and aligned with the main environmental drivers of change (e.g. grazing, fire, climate variability, hydrological regimes) that shape habitat dynamics.

Further research and knowledge improvement needs

Improving Data Collection by leveraging new technologies: The combined use of field surveys and remote sensing tools has proved helpful for monitoring habitat condition and should be further explored. Tools such as satellite image analysis (NDVI) and laser scanning technologies (LiDAR) can provide more precise data on habitat structure and functioning.

These technologies enable measurements of biomass, canopy cover, and regeneration after disturbances.

Addressing Gaps

Extending the assessments to include the main functional animal groups: Most ecosystem functions rely on specific invertebrate communities. Measuring Pollinator diversity and abundance, predator densities, soil decomposing invertebrates, and effects of habitat fragmentation in (micro)habitat mosaics.

Integrating fire regime metrics: Because fire is a key factor in many shrub and scrub habitats, consistent, quantitative methods are needed to assess its frequency, intensity, and effects on biodiversity and habitat structure.

Enhancing landscape connectivity analysis: Fragmentation and connectivity loss affect habitat functionality. Measuring metrics such as patch size, patch spacing, and fragmentation will help identify priority areas for restoration.

Long-term monitoring

Establishing long-term monitoring stations: Creating permanent plots will enable long-term observation, which is key to assessing the success of interventions and habitats in responding to climate change and human activities.

Training and stakeholder engagement

Local training: It is fundamental to train local management teams and conservation professionals in the use of standardized tools and methods. This action will ensure that assessments are consistent and of high quality.

Citizen science: Community participation can be a powerful tool for large-scale data collection, especially for tracking indicator species. Education and awareness initiatives can engage local communities in habitat protection efforts.

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ANNEX. Examples of variables used in the EU MS for assessment and monitoring of heath and scrub habitats (from methodologies analysed, non-exhaustive list)

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
1. Abiotic characteristics				
1.1 Physical state characteristics				
Presence and weight of mulch	Not available	Organic horizons collected on a 20x20 cm surface centered on the sampling point, including the leaf litter and mulch layer. C concentration and its content will be determined in a dry sample.	Threshold values not provided	ES (Pescador et al., 2019)
Electrical conductivity of soil	mS/cm	Collection of 5 soil samples with a cylinder of 5 cm diameter by 20 cm depth. Measurement in the laboratory using a conductivity meter and diluting the soil with distilled water (1:5 solution).	Threshold values not provided	ES (Pescador et al., 2019)
Soil compaction	Not indicated	Estimation of penetration resistance in the required habitat types by using a penetrometer at 5 sampling points per plot, adjacent to the sampling points. .	Not provided	ES (Pescador et al., 2019)
Soil texture	Texture classes	Field and laboratory measurements on soil samples. Soil texture can be characterized as: sandy soil, clay, loam…	Not provided	ES (Pescador et al., 2019)
Soil organic layer thickness	cm	Soil samples are taken with a digging spoon or steel pipe. The thickness of the organic layer is indicated in cm. Four partial samples from each sample field are collected.	Not available	DK (Fredshvan et al., 2019)
Soil depth	cm	No methods provided.	Not provided	RO (Deak et al., 2014)
Soil humus types	Humus types	Presence of humus types: mor, moder and mull.	Not provided	RO (Deak et al., 2014)
Soil submersion	Absence/presence of submersion	Not available	Not provided	RO (Deak et al., 2014)
Erosion	%, partly non-metric	Form (depth, etc.) and extension (% for the sampled area) of erosion is estimated	Not provided	HU (Varga et al., 2021), GR (Dimopoulos, 2018)
Terrain aspect	NA	Measured by compass during field observations/vegetation survey	Not provided	RO (Deak et al., 2014). HU (Vargas et al., 2021)

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
1.1 Physical state characteristics				
Slope degree	degrees	Measured by clinometer during field observations or derived in GIS from DEM	Not provided	RO (Deak et al., 2014)
Geological substrate	Substrate type	Field observations/geological maps at different scales	Not provided	RO (Deak et al., 2014). CY (Dimopoulos & Tsiripidis, 2013)
Skeletal soils	Percentage (%) of skeletal material in the soil	No methods provided	Not provided	RO (Deak et al., 2014)
Rock outcrops	Percentage (%)	Field observations	Not provided	RO (Deak et al., 2014)
Germination niches (bare soil / bare rock)	Percentage (%)	Seedling recruitment depends on the availability of suitable niches for germination, such as bare soil, peat or sand; rock is less self-evident. This criterion aims to assess the availability of these niches.	FV (plot level): ≥5% bare ground and/or ≥5% bare rock recorded in plot	IE (O'Neil et al., 2018)
Shallow groundwater conductivity	uS/cm	Measured at 25 ºC. No methods indicated	Reference values: 44-280	BE-F (Van Calster et al., 2020)
Hydrological condition		Expert visual assessment	Only for 4010: natural = FV	PL (Perzanowska J. et al. 2015). HU (Varga et al., 2021). CY (Dimopoulos et al., 2013)
Groundwater Average levels	m-mv	No methods are provided	slightly dry = U1; strongly dry, ditches draining = U2 (Perzanowska J. et al. 2015)	BE-F (Van Calster et al., 2020) NL (BIJ12)
1.2 Chemical state characteristics				
Soil pH	pH	Collection of five soil samples will be collected for soil characterization with a cylinder of 5 cm diameter by 20 cm Use a pH meter with temperature control and determine the pH in solution 1:2.5 of a dilute, neutral, soluble salt such as CaCl2 0.01N ES (Pescador et al., 2019)	For 4010: 3,2-4,3 For 5130: 2,9-4,5 BE-F (Van Calster et al., 2020)	ES (Pescador et al., 2019), BE-F (Van Calster et al., 2020), DK (Aarhus Universitet, 2020; Fredshvan, 2019)
Groundwater pH	pH		Favourable range: 4,2-5,8	BE-F (Van Calster et al., 2020), DK (Aarhus Universitet DCE, 2020)

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
Organic matter	Percentage (%)	Collection of five soil samples with a cylinder of 5 cm diameter by 20 cm depth is obtained, for which a steel volumetric probe may be used. Each sample will be mixed and homogenized. Determination of the concentration of oxidizable organic matter in mineral soil by the Walkley-Black method or modifications of this method.	Reference values not indicated	ES (Pescador et al., 2019)
Shallow groundwater content of chemical components	mg/L	Measurement of Ammonium, Calcium, Potassium, Nitrate, Orthophosphate, sulphate; hydrogen carbonate.	Favourable values: Ammonium: <0,31; Calcium: 0,7-16; Potassium: 0,5-6,6; Nitrate: <1,05; Orthophosphate: <0,04	BE-F (Van Calster et al., 2020)
Soil nutrient content	Various: see reference values	Concentration of different nutrients is assessed: P (mg P/Kg), Al/Ca, Am/N (Kg/Kg), Fe/P (Kg/Kg), exchangeable cations Ca, K, Mg (cmol/Kg).	Favourable values P (mg P/Kg): < 5,75. Ca/Al: 1 - 15. NH 4 + /NO 3 (Kg/Kg): 1,5-14. Fe/P (Kg/Kg): 4-33. Exchangeable cations Ca, K, Mg (cmol/Kg): 0,4-7,5	BE-F (Oosterlynck, 2019; Van Calster et al., 2020)
Nitrogen content in dwarf shrubs	%	To be measured at plot level. Methodology not specified.	4010 < 1.4 or 1.6 (relaxed criterion) 4030 < 1.4 or 1.8 (relaxed criterion)	DK (Aarhus Universitet DCE, 2020)
C/N ratio		Dry soil samples sent to the laboratory (10 g)	NA	DK (Fredshvan et al., 2022)
N:P ratio		Measured on five mineral soil samples collected. The measurement of both properties should be done in the laboratory. Kjeldahl method for N determination or Olsen and Bray for P determination can be used.		ES (Pescador et al., 2019). DK (Aarhus Universitet DCE, 2020)
Nitrogen deposition	N ha-1 y-1	Nitrogen deposition measured every 6 years	“High”: if < 15 kg or < 1070 mol	NL (BIJ12)
Ellenberg's nutritional indicator	Ellenberg values	To be measured at plot level. Methodology not specified.	“Medium”: if 15-30 kg or 1070-2130 mol	DK (Aarhus Universitet DCE, 2020)
2. Abiotic characteristics				
2.1 Compositional state characteristics				
Characteristic or typical species	Number	The more commonly used methods are visual inspection and expert assessment based on lists of species.	For 4080: A = at least 10 sample patches with 3 or 4 habitat typical species OR at least 5 sample patches regularly spaced in habitat with 3 habitat typical species	AT (Ellmauer et al 2020b); BE (Oosterlynck et al, 2020), BG (MOEW, 2013), CY (Dimopoulos & Tsiripidis 2013), CZ (Lustyk 2023), DE

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
		Species groups include fern and vascular species, Sphagnum moss species, xerothermic heath species (5130). Most methodologies understand as typical species: Diagnostic species, dominant species and frequent species (CY: Dimopoulos & Tsiripidis, 2013)	B = at least 8 habitat patches with 3 or 4 typical species OR at least 3 regularly spaced in habitat area with 3 typical species; C = does not meet threshold B (BfN 2017)	(BfN 2017), IE (Perrin et al., 2014), PL (Mróz 2010, PL (Perzanowska et al. 2015). HU (Vargas et al., 2021). IT (Angelini et al., 2016)
Perennial species richness and abundance	%	All tree, shrub and herbaceous perennial species present in each of the sampling plots will be identified and given an approximate abundance (in %). The abundance of each woody species will be estimated from their intersection (by segments) in several transects. The number and length of these transects will be detailed according to the characteristics of the habitat type, although a minimum of five 10 m transects oriented in the direction of maximum slope, parallel to each other and 2.5 m apart, will be marked and georeferenced.	Not provided	ES (Pescador et al., 2019), GR (Dimopoulos, 2018)
Key, exotic, endemic and functional species	Presence/Number	Identification and quantification from species inventories. Functional types related to growth form, foliar phenology, reproductive and dispersal characteristics, etc.	Not provided	ES (Pescador et al., 2019)
Fauna species	Presence, number	Sightings, reports and censuses of entomofauna, avifauna and mammals (IT) Not provided (ES)	Not provided	IT (Angelini et at. 2016); NL (BIJ12); ES (Pescador et al., 2019)
Flora and Fauna	Number of qualifying species	Inventory of species from 3 species groups and Red List species from 10 other groups every 6 years	“High”: if at least 11 qualifying species occur of which 6 species at over 15% of the surface from each species group; “Medium”: if 5-11 qualifying species occur or more but not all demands of "High" are met; “Low”: if the criteria of the “High” or “Medium” are not met.	NL (BIJ12)
Invasive alien species and native expansive species	% or presence	Visual assessment	For 4010 and 4030: FV < 10% < U1 < 30% < U2 PL (Perzanowska et al. 2015)	PL (Perzanowska et al. 2015), BG (MOEW 2013), DK (Aarhus Universitet DCE, 2020)
Bryophyte or non-crustose lichen species present	Number	Visual inspection, counting number of bryophyte or non-crustose lichen species present, excluding *Campylopus* spp. and *Polytrichum* spp	FV: ≥ 3	IE (Perrin et al., 2014)

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
Negative species	%	Assessed in the baseline survey using a different suite of species. In 2017, any non-native species and species indicative of agricultural improvement, such *as Lolium perenne* and *Trifolium repens*, were assessed as negative species. Scrub species such as *Corylus avellana* and *Rubus fruticosus*, which were regarded in the baseline survey as negative species, were not considered negative in 2017 as they might act as nursery species for Juniper (	FV plot level: ≤10% cover of negative species in plot site level: ≥50% of stops pass the criterion	IE (Perrin et al., 2014)
Floristic composition similar to the *Ziziphus lotus* scrub communities	%	Visual inspection in the field - (*Crataegus azarolus* subtype) - For 5330	Not provided	CY (Dimopoulos & Tsiripidis 2013)
Scrub communities, of pre-forest character with non-significant disturbances;	%	Visual inspection in the field - characterized by typical floristic structure (*Genista fasselata* subtype) For 5330	Not provided	CY (Dimopoulos & Tsiripidis 2013)
Ellenberg's nutritional ratio	Ellenberg value	To be measured at plot level. Methodology not specified.	Good condition < 0.85 or 0.95 (relaxed criterion)	DK (Aarhus Universitet DCE, 2020)
Habitat ruderalization	%	In each polygon, the presence and cover of ruderal species which form independent cenoses or their total coverage exceeds 20% of the area is recorded (*Falcaria vulgaris, Artemisia austriaca, Elymus repens, Achillea millefolium gr., Cynodon dactylon Cichorium inthybus, Euphorbia cyparissias, Cephalaria transilvanica, Daucus carota, Xeranthemum* spp.). Optional for 4070, 4080.	Favorable: Ruderal species do not form independent cenoses on the landfill, and shrub and tree vegetation does not increase. Ruderal and/or replacement species cover up to 10% of the area of the polygon monitored Unfavorable-inadequate: ruderal and/or replacement species cover from 10.1% to 25% of the area of the polygon. Bad: ruderal and/or replacement species cover more than 25.1% of the area of the polygon.	BG (MOEW 2013)
2.2 Structural state characteristics				
Low woody cover (< 5 m)	%	Targeting only the species on a list, estimate the cover of low woody species, whose height is less than 5 m by visual estimation. The cover of the targeted low trees can also be noted thanks to a phytosociological or floristic survey carried out at the plot scale. detail of species to take into account (Mistarz and Grivel, 2020).	<10%=0; 10<%<75=-15; >75%=-30 FR (Mistarz and Grivel, 2020).	FR (Mistarz and Grivel, 2020). BE- F (Oosterlynck, 2020)

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
Tree cover (> 5 m)	%	Visual assessment of the cover of tall trees, i.e. the tree layer (> 5 m). A simple visual estimate of the cover of the tree layer at plot or polygon level will be carried out. The cover of tall trees can also be noted thanks to a phytosociological or floristic survey carried out at the plot scale (Mistarz and Grivel, 2020).	<5%= 0 5<%<15=-5 >15=-10 FR (Mistarz and Grivel, 2020).	FR (Mistarz and Grivel, 2020). BE- F (Oosterlynck, 2020)
***Molinia* coverage**	%	Visual assessment of the cover of *Molinia caerulea* within the plot. The cover of the species can also be noted by means of a phytosociological or floristic survey carried out at the plot level.	<50%=0 >50%=-15	FR (Mistarz and Grivel, 2020)
Eagle fern cover	%	Visual assessment of the cover of *Pteridium aquilinum* at the plot level. The cover of the species can also be noted thanks to a phytosociological or floristic survey carried out at the plot scale (same plot used to estimate the cover of *Molinia caerulea* should be used). It is also recommended to note the presence or absence of management of this species, but this should not be included in the It is also recommended to note the presence or absence of management of this species, without this being part of the scoring. This is to indicate whether management efforts should be started or if they should be intensified. Note: it is strongly recommended to use a flora adapted to the local context when available, in case of doubt.	0 =0 <25=-20 >25=-40	FR (Mistarz and Grivel, 2020)
Coverage of structural and typical species	%	Targeting only the species on a list, estimate their cover within the plot through a phytosociological or floristic survey carried out at the plot scale (Mistarz and Grivel, 2020). The same plot used to estimate the cover of *Molinia caerulea* should be used. It is advisable to note the exact value of the total cover of the structuring species, as well as the species present on the survey form. List of species: *Calluna vulgaris (L.), Hull Erica ciliaris L., Erica tetrali*x L. Ulex gallii Planch - only present in 4020*. Ulex minor Planch.	> 50 =0 [25-50] =-5 < 25 =-10 FR (Mistarz and Grivel, 2020)	FR (Mistarz and Grivel, 2020). DE (BfN, 2017). IE (Perrin et al., 2014). BE (Delescaille et al., 2021)
Volume of juniper trunks (only for 5130)	m	Volume of the thickest juniper trunks at chest height (m)		LT (Rašomaviÿius et al., 2015)

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
Cover of mosses, lichens and open soil (only for 4030)	%	The projected coverage of mosses and lichens and the proportion of open soil in the transect are evaluated separately (%)	Not available	LT (Rašomaviỹius et al., 2015)
Height of tree, herb and scrub layer	m	Visual expert assessment	For 5130: FV > 0.8 > U1 > 0.2 > U2. PL (Perzanowska et al. 2015)	CY (Dimopoulos & Tsiripidis, 2013).PL (Perzanowska et al. 2015)
Structural analysis of the stand	Stratification, diameters heights, etc.	Analysis of the vertical structure of the standby means of dendrometric surveys (measurement of the diameters of species diameters of tree and shrub species, count of individuals of dominant or typical tree species according to their respective diameter).	Not provided	IT (Angelini et al., 2016)
Age structure	%	Expert judgement. Reference to literature source Van der Ende (1983) for description of phases. Phases: Pioneer, = 0-6 years after vegetation removal ("plaggen"/ sod cutting) - young heather shoots and high proportion of ephemeral species; development - 6-12 years with full grown heather plants but still some pioneer plants; maturity - large dense heather plants and no pioneer species; degeneration - starts after 16-30 years (depending on nutrient deposition) with loss of vitality of heather plants. NB small sites can be classed as B even if only the development or mature age phase is present. DE (BfN 2017)	A = all four age phases present and degeneration phase on 50% or less B = two to three age phases present or degeneration phase takes up 50-75% of area C = only one age phase or degeneration phase on more than 75% of area. DE (BfN 2017)	BE-F (Van Calster et al., 2020), DE (BfN 2017). CZ (Lustyk et al., 2023)
Coverage of invasive species and disturbance indicators	%	Indication of the relative proportion of invasive neophytes (according to ESSL & RABITSCH 2002) and disturbance indicators within the study area. AT (Ellmauer et al 2020b)	A. Coverage of disturbance indicators and invasive neophytes: < 10%; B. Coverage of disturbance indicators and invasive neophytes: 10 - 20%; C. Coverage of disturbance indicators and invasive neophytes: >20% (Ellmauer et al 2020)	AT (Ellmauer et al 2020), LV (DAP, 2023), DK (Aarhus Universitet DCE, 2020), LT (Rašomaviỹius et al., 2015), IE (Perrin et al., 2014). BE (Delescaille et al., 2021 and Oosterlynck et al., 2020)
Woody Plant Coverage: trees, shrubs, typical willow species		This indicator is recorded in the field form. For each polygon, the presence of species of trees and shrubs is noted (Crataegus *monogyna, Prunus spinosa, Rosa spp., Acer tataricum, Fraxinus ornus, Cotinus coggygria*) (MOEW 2013)	Favourable: 4030 <30%; 4060, 4080,40A0,40B0 <10% (MOEW 2013)	BG (MOEW 2013), DE (BfN 2017), AT (Ellmauer et al 2020b), PL (Perzanowska et al. 2015), LV (DAP, 2023), DK (Aarhus Universitet DCE, 2020), IE (Perrin et al., 2014)
Open area without trees or scrubs coverage	Proportion of area (%)	Visual inspection. Every 6th year. LV (DAP, 2023)	A = 5-25% B - 1-5% or 25-40%	LV (DAP, 2023), DE (BfN 2017)

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
			C = missing or over 40% DE (BfN 2017)	
Total projective coverage of cenosis	Brown-Blanquet scale	Within the reporting site boundaries, all plant species are identified and recorded on the form. Each species is given an abundance/cover score on the combined seven-point Brown-Blanquet scale	Favorable: 4030,40B0. More than 80% projective coverage of phytocenosis with the dominant shrub species of the polygon. 4060,4090, 40C0. >60% Optional for 4070, 4080	BG (MOEW 2013). IT (Angelini et al., 2016)
Senescent proportion of *Calluna vulgaris* cover	% cover	Visual inspection in the field.	FV; cover < 50%	IE (Perrin et al., 2014)
Growth phases of *Calluna vulgaris*	classes	Outside boundaries of sensitive areas, all growth phases of Calluna vulgaris should occur throughout, with	FV: ≥ 10% of cover in mature phase	IE (Perrin et al., 2014)
2.3 Functional state characteristics				
Net primary production	g C m−2 yr−1	Quantification of primary production by perennial plants in each plot using extensive sampling systems such as remote sensing.	Not specified	ES (Pescador et al., 2019)
Recruitment	low, medium, high	Semi-quantitative density estimation of recruitment at the plot level, based on two categories: (1) plants older than one year with no signs of lignification and (2) recruited individuals, lignified, but not fully reached the reproductive stage. Mainly for key species	Does not specify reference levels for each density category nor values for each habitat type.	ES (Pescador et al., 2019)
Damage - Defoliation	Presence/absence. and degree of importance	Identification and quantification of the main phytosanitary damages: 1 No damage. 2 Unknown causes 3. Biotic: a) defoliation b) agents: fungi, insects, plans, cattle or other fauna. 4. Abiotic: a) climatic agents: snow, wind, draught, lightning, ice, rain. b) others: fire, erosion, landing.	Damage - Importance of damage: Low = 1, Medium = 2, High = 3.	ES (Pescador et al., 2019)
Carpet of dead organic matter	cm	Visual expert assessment	FV < 10 < U1 < 15 < U2	PL (Perzanowska et al. 2015)
Dead trees	Proportion % from total count of junipers (for 5130)	Visual inspection. Every 6th year. Only for 5130: dead junipers, dead trees (standing or fallen) from ancient, wooded meadow landscape in 2nd layer and undergrowth, Dead trees and stumps >50 cm	Not provided	LV (DAP, 2023)
Individuals berried	%	Assessed in the baseline survey; examines the potential for reproduction in the formation by setting a	FV: at stop level: ≥10% of Juniper shrubs rooted in plot are buried; at	IE (Perrin et al., 2014)

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
		threshold for the proportion of mature, reproducing female shrubs in the formation	site level: ≥50% of stops pass the criterion	
Seedlings	%	Assessed in the baseline survey; examines the level of seedling recruitment in the formation by setting a threshold for the number of seedlings found in the formation. Because of the difficulty in determining the age of Juniper plants it was decided to confine this criterion only to plants that were undeniably seedlings (<15cm tall with minimal side branching).	FV (at plot level): >0%, i.e. at least 1 seedling recorded in plot at site level: >0% of stops pass the criterion	IE (Perrin et al., 2014)
Individuals alive	%	Assessed in the baseline survey; examines the level of die-off of individual Juniper plants in the formation.	FV (plot level): ≥90% of Juniper shrubs rooted in plot are alive site level: ≥75% of stops pass the criterion	IE (Perrin et al., 2014)
Browning	%	Not assessed in the baseline survey. While die-off assesses the level of whole plant death in the formation, examining the prevalence of die-back, or browning, may also provide an early indication of problems in the formation, for example, due to factors such as fungal disease (e.g. *Phytophthora austrocedri*, a pathogen currently causing problems in the UK's Juniper stands (Forestry Commission, 2017); note: referred to as *Phytophthora austrocedrae* in some publications, e.g. Ward & Shellswell (2017)) or water stress. Browning is calculated as the percentage cover of Juniper within the plot that is dying back due to stress. Calculated as: (% browning in plot / % Juniper in plot) x 100	FV (plot level): ≤20% of Juniper in plot is browning site level: ≥75% of stops pass the criterion	IE (Perrin et al., 2014)
Succession stages	Presence and abundance	Evidence of primary or secondary succession	A = not noticeable B = at edge or in small areas and can be counteracted with simple management measures C = advanced succession only manageable with intensive interventions DE (BfN 2017)	DE (BfN 2017), GR (Dimopoulos, 2018), CY (Dimopoulos et al., 2013). AT (Ellmauer et al., 2020)
Recovery of Juniperus communis (only for 5130)	Not provided	A resurgence of juniper is observed in the monitored area.	Not provided	BG (MOEW, 2013)

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
Management	Intensity scale	Visual assessment. Intensity of use (mowing, grazing) is assessed	0 – none, 1 – non-intensive, 2 – medium, 3 – intensive LT (Rašomaviÿius et al., 2015)	CZ (Vydrová and Lustyk, 2014), LT (Rašomaviÿius et al., 2015), LV (DAP, 2023)
Grazing	Proportion of area (%)	Visual inspection. Every 6th year.	Not provided	LV (DAP, 2023), RO (Deak et al., 2014), GR (Dimopoulos, 2018)
3. Landscape characteristics				
Fragmentation by infrastructure	% of area affected	Specification of the area (in %) that is affected by infrastructure facilities (e.g. hiking trails, (forest) roads, lift systems, etc.). The reference area is the entire individual occurrence or that part of the individual occurrence that lies within the sample area. AT (Ellmauer et al 2020b)	A. No Fragmentation of the stand through infrastructure. B. small-scale cutting of stand through infrastructure (< 5%). C. Distinct cutting of stand ock through Infrastructure (> 5%) AT (Ellmauer et al 2020b)	AT (Ellmauer et al 2020b), PL (Perzanowska et al. 2015), DE (BfN 2017), LT (Rašomaviÿius et al., 2015), GR (Dimopoulos, 2018)
Landscape environment	m (distance), m2 (size of the habitat) and non-metric	Description of the rate of isolation (subjective), the distance of the similar habitats, the size of the sampled habitat patch, the role of the neighbouring habitats (friendly or non-friendly), the presence of potential invaders and the regeneration potential of the vegetation (subjective) in the sampled area.	Not available	HU (Varga et al., 2021). IT (Angelini et al., 2016). NL (BfN12). CY (Dimopoulos et al., 2013)
Ecotonic zones	Descriptive	Describe in a polygon the nature of the transition of the habitat to other natural or seminatural plant communities (width of the transition zone, type of neighbouring communities, use etc)	Not available	LT (Rašomaviÿius et al., 2015)
Mosaic	Presence or absence	5130: Indicates whether the transect contains natural habitats (yes, no)	Not available	LT (2015)
Habitat cluster area	ha	Applicable only in essential and very important areas	For 4010 and 5130: Favourable condition: ≥ 75 ha For 4030: Favourable condition: ≥ 50 ha	BE-F (Oosterlynck et al., 2020)
Specific habitat area in a habitat cluster	ha	Applicable only in essential and very important areas	Favourable condition: ≥ 5 ha	BE-F (Oosterlynck et al., 2020)

Variable name	Metrics	Measurement methods	Examples of thresholds	MS and references
4.Other				
Disturbances. afforestation, trampling and browsing, footsteps, substrate relocation, drainage.	%	Etimate % coverage in relation to whole of defined habitat area. DE (BfN 2017)	A = 0% B = more than 0% up to 5% (single shrubs or trees) C = more than 5% v	HU (Varga et al., 2021), DE (BfN 2017). AT (Ellmauer et al., 2020), BE-F (Oosterlynck et al., 2020)
Degradation	Intensity scale (0, 1, 2, 3, W)	Visual inspection and estimate of habitat degradation from signs detected in the field.	0 – habitat without manifest signs of degradation or degradation degree is insignificant; 1 –low degree of habitat degradation; 2 – medium degree of habitat degradation or the degree of degradation is spatially very different; 3 – high and significant degree of habitat degradation; W – very high degree of habitat degradation and tendency towards unnatural habitat; keywords – according to List of pressures and threats under Article 17 of the Habitats Directive; subjective assessment (mapper directly in the field)	CZ (Lustyk et al., 2023)
Anthropic signs of disturbance/ degradation	Presence/absence- not specified	For this purpose, all anthropogenic signs (iteration by trampling, machinery or surrounding constructions and works, presence of residues and spills, signs of cutting,) will be visually identified within a radius of 50 m from the center of each plot.	Anthropic Signs - Degree of Threat: Small 1, Medium 2, Large 3	ES (Pescador et al., 2019)
Damage by *Cydalima perspectalis* or fungal infection *Cylindrocladium buxicola*	frequency	Visual inspection in the field.	A = none; B = sporadic or few individual bushes affected; C = widespread invasion / infection and box dieback or loss of foliage	DE (BfN 2017)

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