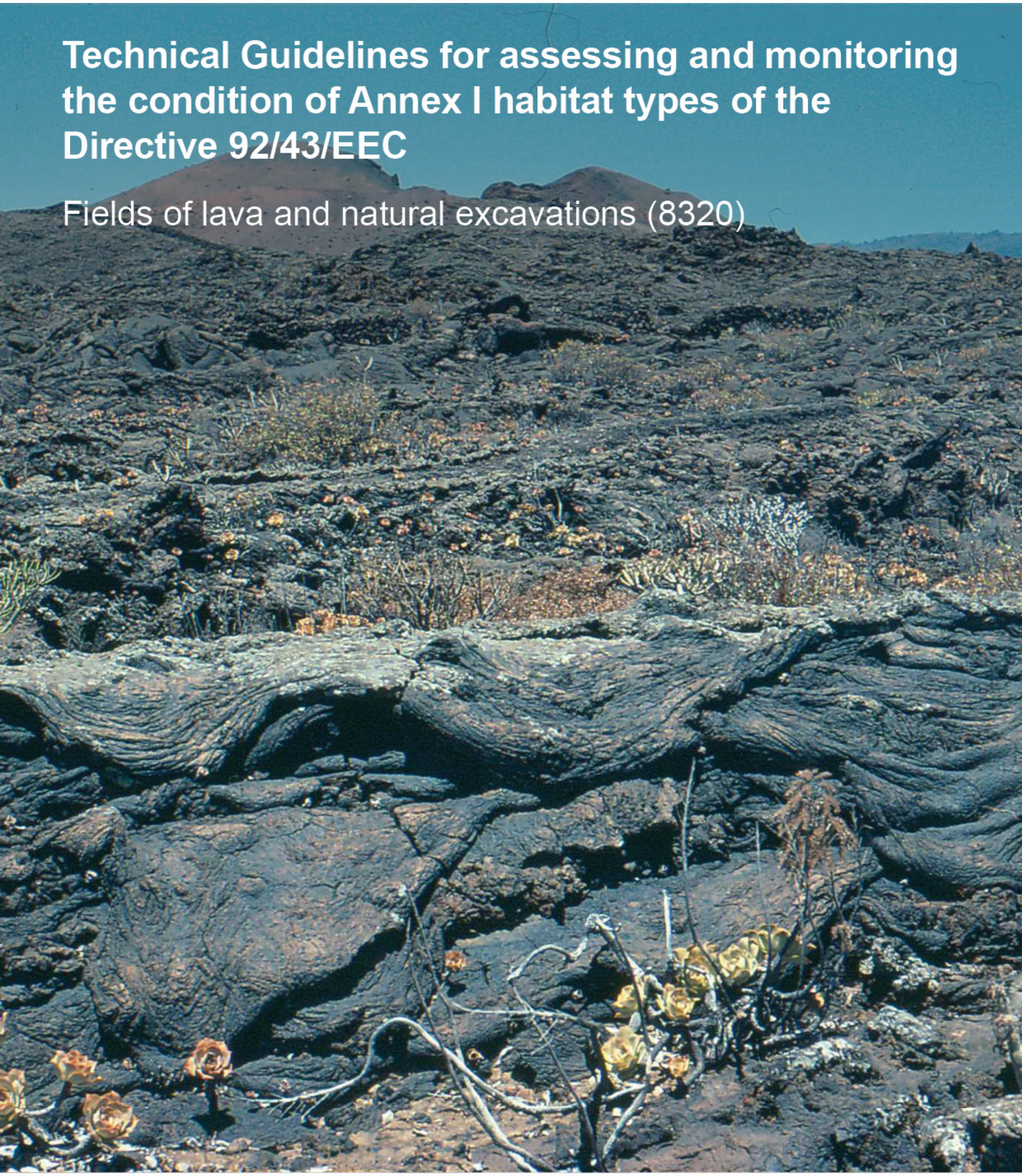
European Commission

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

Fields of lava and natural excavations (8320)



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

Fields of lava and natural excavations (8320)

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This document must be cited as follows:

Pérez-Alberti, A., Šibík, J. & Zuazu Bermejo, A. (2025) Fields of lava and natural excavations (8320). In: C. Olmeda & V. Šefferová Stanová (eds.), Technical guidelines for assessing and monitoring the condition of Annex I habitat types of the Directive 92/43/EEC. Luxembourg: Publications Office of the European Union, ISBN 978-92-68-32016-7 https://doi.org/10.2779/3245560

Manuscript completed in September 2025

Luxembourg: Publications Office of the European Union, 2025

PDF ISBN 978-92-68-32016-7 doi:10.2779/3245560 KH-01-25-201-EN-N

Contents

Acknowledgements

This document was prepared in the framework of a European Commission contract with Atecma, Daphne and the IEEP for the elaboration of Guidelines for assessing and monitoring the condition of Annex I habitat types of the Directive 92/43/EEC (Contract nr. 09.0201/2022/883379/SER/ENV.D.3).

Concha Olmeda (Atecma) and Viera Šefferová Stanová (Daphne) coordinated a team of scientific experts that elaborated the guidelines for all habitat types, and provided input during their preparation. In particular, they prepared the Overall Methodology, from which some texts are included, with adaptations, in these Technical Guidelines (e.g., sections 1.3, 3.2, 3.3 and 3.6).

An ad-hoc group of experts nominated by Member States administrations, the European Topic Centre for Biodiversity and Ecosystems (ETC-BE), the Joint Research Centre, EuropaBON, the European Environment Agency and the European Commission, provided advice and support throughout the development of these technical guidelines.

Several members of the project team, of an ad-hoc group supporting the project, experts and representatives from EU Member States authorities and other relevant organizations revised the drafts and helped refine this document. Particularly useful were the insights provided by Axel Ssymank (ETC-BE, German Federal Agency for Nature Conservation, BfN).

All those contributions are gratefully acknowledged.

Glossary and definitions

Habitats

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

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

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

Species

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

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

Variables

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

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

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

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

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

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

Abbreviations

EU**:** European Union

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)		

Executive summary

Volcanic surfaces result from recent eruptive activities across European terrestrial volcanic landscapes. The habitat is distinguished by its specific geological formations: extensive lava flows, volcanic cones, and natural depressions that result from explosive eruptions or the collapse of volcanic edifices. The terrain is typically characterized by high thermal fluctuations, a sparse distribution of vegetation, nutrient-poor substrates and limited moisture availability.

Their ecological characterization is given by the climatic conditions, chemical composition of magma and topographic characteristics. The Habitats Directive collects volcanic terrestrial environments under habitat type 8320 Lava fields and natural excavations which includes barren lava fields, lava tubes and fumaroles.

The analysis of existing methodologies across EU Member States was based mainly on the methodologies developed by Spain and Italy, which present a high level of similarity. The abiotic characteristics measured focus on magma characteristics, lithology and the chemical characteristics of the substrate. Composition and structural characteristics are assessed through the presence and coverage of characteristics and dominant plant species and communities, as well as presence of sulphobacteria and algae. Presence of functional processes like flowering and seed production of typical species is measured. Analysis of the habitat landscape characteristics has not been addressed in the consulted methodologies. Thresholds for interpreting these metrics are absent. Similarly, only one of the consulted methodologies includes an aggregation system. Monitoring procedures are largely based on periodic field observations.

A set of essential, recommended and specific variables for monitoring this habitat are proposed. They are categorized into abiotic (e.g. rainfall distribution, type of pyroclastic material, chemical and mineralogical composition of the substrate), biotic (e.g. presence and abundance of mosses, lichens, vascular plants), structural (e.g. cover of vegetation groups), functional (e.g. flowering and seed producing species), and landscape (e.g., patch size, fragmentation).

The guidelines outline several priority areas for future effort, beginning with the thorough testing of the proposed variables and measurement procedures using common protocols. A central objective is the development of standardised methods for establishing ecological thresholds and reference values to assess habitat condition, which is vital for monitoring change and anthropogenic impacts. Concurrently, criteria must be refined for selecting monitoring localities and for aggregating local-scale results to the biogeographical level to ensure data is representative and comparable. Finally, harmonised approaches for using typical species as key indicators of habitat status should be formally established and integrated into the overall condition assessment.

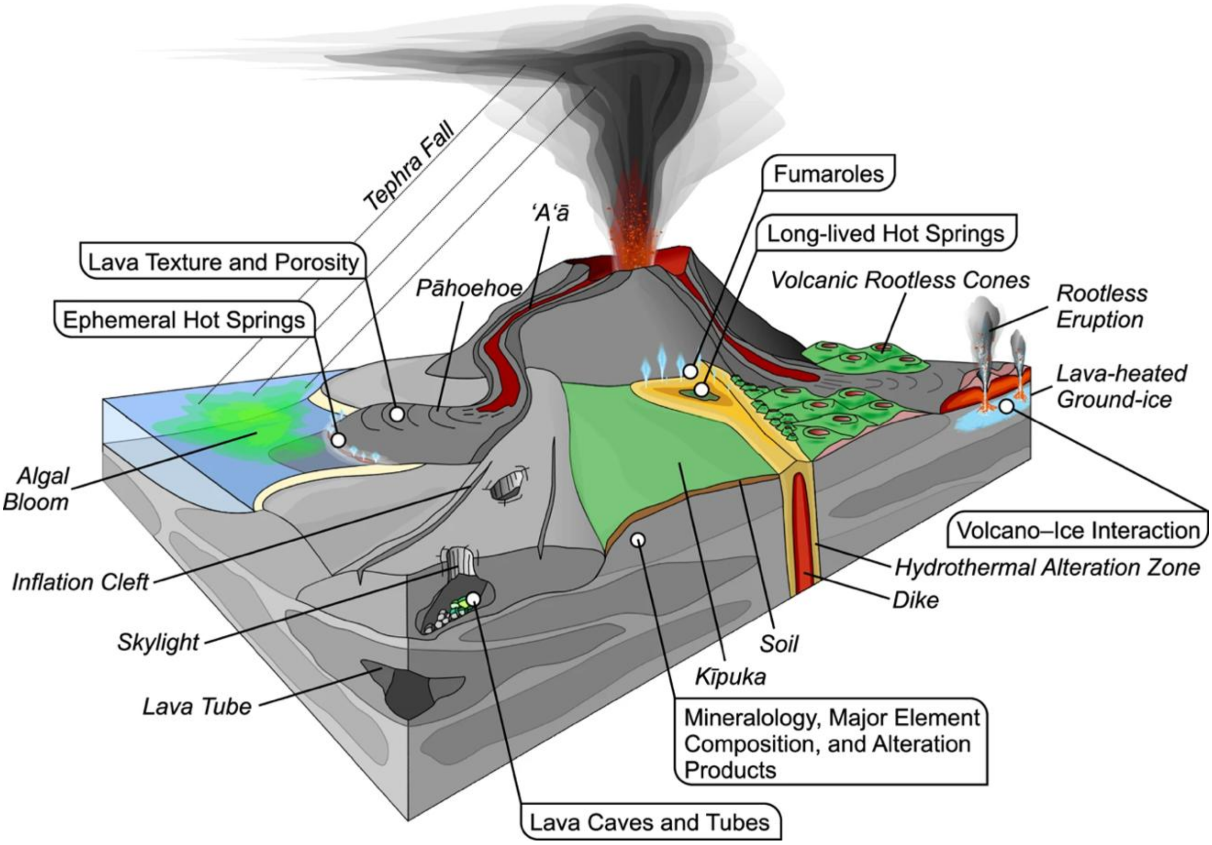
1. Definition and ecological characterisation

1.1 Definition and interpretation of habitats covered

This habitat type corresponds to terrestrial volcanic surfaces resulting from recent eruptive activities across Mediterranean, Macaronesian, and temperate volcanic landscapes. The habitat is distinguished by its specific geological formations, which include extensive lava flows, volcanic cones, and natural depressions that result from explosive eruptions or the collapse of volcanic edifices. They include complex lava tube systems, diverse geothermal features (Figure 1).

The terrain is typically characterized by a sparse distribution of vegetation, consisting of plant species that have evolved to endure the challenging conditions presented by volcanic soils. These conditions often include high thermal fluctuations, nutrient-poor substrates, and limited moisture availability. Commonly observed flora consists of various succulent plants, resilient lichens, and hardy mosses that adeptly colonize the rugged rocky surfaces. Beyond its unique plant life, it also harbours a diverse range of fauna, mainly specialized insects and small mammals adapting to thrive in these rugged and often harsh environments. The presence of wildlife enhances the ecological complexity of the habitat. Furthermore, this habitat plays a vital role in studying ecological succession, offering valuable insights into the processes through which life re-establishes itself following volcanic disturbances.

Figure 1. Habitats for biota associated with volcanic terrains



The figure depicts a complex volcanic system representing several lava-associated formations: long-lived and ephemeral hot springs, fumaroles, lava tubes, and lava rocks, as well as melted ice and associated products from lava–ice interactions.
Source: Hadland et al. (2024).

Two main types of material, lava and pyroclastic material, are produced as a result of eruptive volcanic activities. The materials ejected during explosive eruptions are named pyroclasts (meaning “fire-broken” from ancient Greek) and can be classified according to its size into: powder, ashes, sand, lapilli or fragments.

Lava flows exhibit numerous broken surfaces and their fronts tend to advance as individual units. Block fronts collapse, giving rise to mounds of debris from the early stages of formation and thickening as they move forward, often reaching more than 10 times their initial thickness. In addition to the rupture of the flow, its thickening can lead to the overflow of lava flows towards its lateral margins, which can generate superimposed accumulations, giving rise to complex and differentiated spaces. On the other hand, lava channels, which flow under the surface, can become tubes that can reach kilometres in length when the lava stops flowing.

The spectrum of surface textures of lava fields is large, and identical lava compositions may create different surface shapes depending on the viscosity, speed and regularity of the flows (Gates & Ritchie, 2006). Two types of lava have generally been described, “aa” and “pahoehoe”, names originating from Hawaii. “Aa” lava (which received this name because walking over them barefoot made you exclaim "ah-ah" in pain) presents numerous projections and edges, while “pahoehoe” lavas (from the Hawaiian term used for rope) have a softer texture composed of coalesced flows that accumulate creating shapes like intertwined ropes.


Left: Aa lava flows. Teide Canyons (Tenerife). Right: Pahoehoe lava flows. Tenerife.
Source: Augusto Pérez Alberti

The formation of volcanic tubes is linked to the cooling and consolidation process of lava flows and is a result of the contact of the surface of the lava flow with the atmosphere and of the contact of its base with the ground surface through which it circulates. This loss of temperature favours its external consolidation, while its interior remains in a molten state in which the magma flows without obstacles. When the lava flow decreases, internal voids can be created that form authentic underground galleries.

Volcanic tubes can appear in any of the described lava flows, although they are generally associated with basaltic fluid flows, such as pahoehoe and aa lavas. This does not mean that they cannot develop from flows of magmas with a more dynamic flow, from changes in the flow of lava, due to the topography and other factors (Beltrán & Doniz, 2009). Volcanic caves are part of the eruptive phenomenon.

In addition to the different types originated by lava flows, other particular habitats produced by secondary volcanic activities are present in various volcanic areas, including hot springs, fumaroles, solfataras and cinder cones (see Figure 1).

This habitat type is characterized by its unique geological features, primarily consisting of lava fields and areas of natural excavation. These environments are typically devoid of significant vegetation due to the harsh conditions and the nature of the substrate (Chytrý et al., 2020; Galparsoro et al., 2012). While this is true for vascular plants on younger lava flows in arid regions, in older lava flows in cooler and wetter climates biological colonization can be extensive, especially by cryptogams. Lichens, particularly from the genus *Stereocaulon*, often dominate the early stages of colonization (Kristínsson & Heiðmarsson, 2009). Their resilience to extreme dryness and temperature shifts allows them to form dense mats that help stabilize the lava surface.

The species composition in these habitats is often limited due to the challenging living conditions. However, certain specialized species that can tolerate the extreme conditions may be present. The vegetal component in this habitat may be absent or sparse, conditioned by the lack or scarcity of soil and limited to pioneer species specialized in living on lava or incoherent volcanic products, with the ability to tolerate the presence of hot gases and vapours (Angelini et al., 2016). Plant colonisation is also conditioned by specific environmental factors, as soil temperature, humidity and chemical composition (Poli Marchese, 2021).

The Interpretation Manual of EU habitats (European Commission, 2013) defines this habitat type as: sites and products of recent volcanic activity harbouring distinct biological communities, and describes various sub- types:

- communities that form in the summit of the Teide and Etna volcanos;
- barren lava fields, which are almost bare lava formations of other volcanoes, and of lower altitudes on the Etna and Teide, colonized by vegetal communities as well as lichens and invertebrates; volcanic ash and lapilli fields;
- lava tubes, which are caves formed by hollow basaltic tubes resulting from the cooling of the surface of lava flows whose inner molten continued to flow;
- fumaroles, which are orifices in volcanic areas through which hot gases and vapours escape.

This habitat is found in regions with volcanic activity. Active or recently active volcanoes in the EU are localised in the Mediterranean and the Macaronesian regions. The volcanos of Mediterranean area are located in Italy, in the area of Naples, the island of Ischia, Sicily and the Aeolian islands, and Greece in the Aegean archipelago. In the Macaronesian region, the volcanoes are located in the Canary Islands in Spain an in the Azores archipelago in Portugal.

It should be considered that, from the point of view of volcanism, the term recent implies a long period of time and of different duration. For this reason, it is important to highlight that this habitat type includes volcanic surfaces of very different ages and with different degrees of transformation of the original volcanic morphology.

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

1.2.1 Ecological characterization of lava fields

This habitat is characterized by a great diversity of environmental conditions originated from the volcanic activity. Volcanic eruptions are the surface expression of processes occurring deep within the Earth (Gates & Ritchie, 2006). Many of them take place just beneath its outer crust, but some volcanic eruptions occur at greater depths, even at the boundary between the Earth’s core and mantle, 2,890 km below the surface.

The style of volcanic eruptions varies greatly, both between volcanoes and within the same volcano during its eruptive phase. This variety is related to the different types of magma. Magma flows descend at varying rates depending on their viscosity. The more viscous a magma is, the less fluid it is. Therefore, its speed depends on its temperature and composition. Higher-temperature magma, such as basalt, is more fluid (lower viscosity) than lower-temperature magma, such as rhyolite, which explains why basaltic flows tend to travel long distances, whereas rhyolitic magmas accumulate around the volcanic vent from which they erupted.

The extent of landscape transformation in post-eruption volcanic areas is largely determined by the age of the lava flows, assuming consistent climatic conditions and morpho structural settings (Beltrán & Doniz, 2009).

Geomorphological factors operate on a broad spatial scale and at the local spatial scale. In the first case, the relationship with the main morpho structures and main topographic areas, for example volcanic ridges or volcanic fields, must be taken into account. At the local scale, geological factors (type of magma, eruptive style, lithology, age) and geomorphological factors are taken into account.

Abiotic characteristics

Factors associated with magma and lava flows, physical and chemical characteristics

Magmas are a mixture of molten rocks that may contain suspended solid particles and dissolved gases (Sparks, 1993). The **chemical composition** of magma is closely related to the explosiveness of the volcano. The variation in the amount of silica (SiO_2) is used to describe the variation in the composition of igneous rocks and the magmas that formed them. Rocks with little silica (basalt, gabbro) are called mafic rocks while those containing high concentrations of silica (rhyolite, granite) are called silicic or felsic rocks. All magmas contain a small amount of dissolved gas, usually between 0.2 and 3% of the magma volume, as well as carbon dioxide. Gases usually control the explosiveness of a volcanic eruption, as a greater abundance of gases leads to more explosive eruptions. Basaltic magmas, melt at temperatures ranging from 1200 to 1000 ºC, have low viscosities and little gas content; while acidic magmas have melting temperatures between 1000 and 800 ºC, high viscosities and high gas content (Sparks, 1993).

Based on their geochemical characteristics (%SiO_2) rocks can be classified as: *ultrabasic* (<45% SiO_2), *basic* (between 45-52% SiO_2), *intermediate* (between 52-66% SiO_2) and *acidic* (>66% SiO_2). According to the ferromagnesian content (Fe, Mg, Mn and Ti) in: *femic rocks* (>40%) and *salic rocks* (>40%) (Araña & Ortiz, 1984; Sparks, 1993). Therefore, there seems to be a direct relationship between magmas rich in silica and poor in ferromagnesians (acidic/salic) and those poor in silica and rich in ferromagnesians (basic/femic). In situ, rocks can be classified according to their chemistry based on colour: basic, dark colours, intermediate grey and light green, and acidic ochre, brown and whitish.

The role of climate

Climate, particularly **temperature and rainfall**, determine the speed of colonization and impose restrictions on the range of species that can colonize the volcanic substrate. Climate, in turn, is regulated by altitude and latitude and, locally, by **relief, slope and exposure**, factors that influence, above all, the microclimate. The colonisation process is generally shorter where the climate is more humid. Altitudinal climatic changes result in an ecological gradient that influences primary succession (Poli Marchese, 2021).

The distribution of habitat type 8320 in Europe entails an ecological differentiation within and between regions. For example, the presence of recent volcanoes the different climatic conditions of the Canary Islands or the Azores implies a great environmental diversity for this habitat type in the Macaronesian region. Due to the atmospheric and orographic characteristics of each archipelago located at subtropical latitudes on the eastern oceanic margin, the recently formed volcanic surfaces are subject to multiple environmental variations that results in numerous habitat subtypes, depending on the differences in altitude, orientation and their exposure to air currents that are dominant at this latitude, which largely determine their ecological diversity (Beltrán & Doniz, 2009).

Biotic characteristics

Plant colonization processes

The vegetal component in lava flows may be absent or very scarce, it is highly conditioned by the lack or scarcity of soil and is usually limited to pioneer communities, specialized in living on lava or volcanic products, and particularly rich in endemic species, linked to these unique and severe ecological-environmental conditions (Angelini et al., 2016). For instance, on Tenerife's Pico del Teide (Canary Islands), endemic species account for two-fifths of the entire flora found on this volcano (Ceballos & Ortuno, 1951 cited in Poli Marchese ,1982).

Volcanic activity releases products in the form of rocks and surfaces of distinct consistency. The resulting young substrates are usually rich in nutrients, but quite limited in terms of water retention. This motivates colonization by a very characteristic flora adapted to drought, often dominated by lichens and succulent plants capable of accumulating moisture in its roots and stems.

According to Poli Marchese (2021) plant colonization on volcanic surfaces is conditioned by both chemical-physical factors and by biological factors. The material from volcanic activity produces ecologically different substrates, depending on their degree of decomposition and their surface topography.

Different types of lava flows give rise to substrates with different conditions. In general, it can be said that the speed of plant colonization and the resulting soil formation depend largely on the degree of compactness of the substrates. The process is slower in compacted substrate, being faster in pyroclasts substrates than in lava (Poli, 1970).

The age of the lava is one of the most important factors in the process of vegetal colonization, since it imposes limits on the range of species that can colonize the volcanic substrates and also influences their number and development (Léonard, 1959, cited in Poli Marchese, 2021). This factor is, however, less important than others such as the topography of the surface or climatic conditions. Frequently, some lava flows are colonized more quickly than others that are older but more compact and, consequently, with a greater difficulty to be colonized by plants. They can also be colonized faster than other lava flows of the same age but which are subject to a drier climate.

There is no global model for vegetation succession after volcanic activity, because active volcanoes cover a large geographic diversity, vary in magnitude and recovery (del Moral & Grishin, 1999). The recover speed of the system depends on climate, substrate, and landscape factors.

Poli Marchese (2021) has studied and described the primary succession on active European volcanoes where the different habitats and substrata are mainly originated by the volcanic activity. The primary successions take place in different ways, at different rates and involves different plant species according to the geographic area and the history of the local flora. However, a successional pattern is described. Primary succession begins with the most primitive organisms and gradually moves through the most evolved organisms until the settlement of the phanerophytes. On the lava flows the first colonizers are Blue-green Algae and Bacteria thanks to their ability to fix atmospheric nitrogen; this stage is followed by one of Mosses and Lichens that prepares the stage of small herbaceous annuals, while shrubs and trees are establishing only where there is a deeper accumulation of fine material and humus. The different stages are characterized by the interaction of climatic, topographic and biotic factors (Bjarnason, 1991).

Box 1. Primary succession on active volcanic areas in Europe

Adapted from Poli Marchese, 2021

a) **Blue-green algae and bacteria**. The first colonizers of the sterile lava are the blue-green algae (*Cyanophyta*) and bacteria since their ability to fix atmospheric nitrogen makes them independent of the substrate.
b) **Lichens and mosses**. These cryptograms use the first organic substances accumulated in the soil after the decomposition of the first colonizers. The slags, fragments and rough edges of the rocks are colonized by lichens, which soon flower and with the physical-chemical action of their hypothallus help to decompose the substrate.
c) **Vascular plants**. In the small amount of humus formed by the Cryptogam colonies, and sometimes on a layer of moss, small herbaceous vascular plants are established. In particular, there are annual species (dwarf therophytes) that colonize the small surfaces between rocks. Inside deep fissures, where there is a greater accumulation of fine material and humus, woody plants are established, including shrubs and trees that are characteristic of each volcanic area (Poli, 1970). Increased decomposition and the accumulation of other fine materials and humus allow the establishment of other plants vascular, mainly chamaephyte and hemi-cryptophytes. The final stages of the primary succession are characterized by woody plants of which some are also present in previous dynamic stages. In the Etna, for instance, *Genista aetnensis* and *Pinus laricio* are often present in colonization processes from lava (Poli & Grillo 2000).

In **fumaroles**, soil is characterized by higher temperatures and humidity levels, as well as the presence of gases such as hydrochloric acid, sulphur dioxide, carbon dioxide, and ammonium chloride, which are emitted with water vapor. The organisms present in these habitats are highly specialized and distributed in a horizontal zonation, ranging from less evolved to more evolved taxonomic groups, depending on temperature and humidity values. Less evolved taxonomic groups occupy areas with the highest temperature and humidity values, and vice versa. These habitats exhibit a great diversity of taxonomic groups, from cyanophytes to bryophyte, pteridophytes and vascular plants (Poli Marchese, 2021).

This habitat type is characterized by the presence of numerous endemic species that, even though they never reach high coverage values, have a significant phytogeographical significance at a local scale. Therefore, it is possible to identify some target species for monitoring at a regional level, on the basis of the overall floristic composition.

The main ecological characteristics and the associated variables that can be used to assess the habitat condition are presented in Table 1 below. Some of the variables included are not proposed to measure the habitat condition but rather to describe contextual factors that determine the characteristics of the biological communities and can be useful to detect and interpret possible changes along the monitoring.

Table 1. Main ecological characteristics and variables useful for the assessment and monitoring of habitat condition.

Ecological characteristics	Types	Group of characteristics	Examples of variables useful to measures key characteristics
Abiotic characteristics	**Physical state characteristics**	Climatic conditions	- Temperature - Rainfall
		Geomorphological characteristics	- Lava type - Pyroclastic materials - Spatial distribution (cover) of megastructures and direct volcanic forms (cones, craters, lava fields…)
		Topographic characteristics	- Altitude - Orientation
	Chemical state characteristics	Lithology, chemical composition of the substrate	- Rock type based on % SiO_2: ultrabasic, basic, intermediate and acidic
Biotic characteristics	**Compositional state characteristics**	Vegetal community composition Animal species	- Species presence/abundance from different taxonomic groups: algae, lichens, mosses and vascular plants - Presence of alien species - Invertebrate species (incl. endemic species)
	Structural state characteristics	Cover /density of vegetation	- % cover of vegetation / bare substrate - % cover of algae, lichens, mosses and vascular plants
	Functional state characteristics	Successional state Alteration of habitat and ecological processes (colonisation) by human activity	- Temporal development of volcanism - Presence of Nitrophilous species - Damage/degradation by infrastructures, extractive activities and other human activities
Landscape characteristics (connectivity / fragmentation)			- Urban, agrarian occupation and human activities in the surrounding area that affect the habitat and colonisation processes

1.3 Selecting typical species for condition assessment

The Habitats Directive uses the term 'typical species', but it does not give a definition for use in reporting. For a habitat type to be considered in favourable conservation status, the Habitats Directive requires that both its structure functions and its 'typical species' be in favourable status (Article 1(e)).

The assessment of typical species is part of the assessment of the structure and function parameter, however little guidance has been provided on how to use the typical species in this assessment.

The formulation of Art. 1(e) would suggest that the assessment of typical species could be carried out separately and complement the assessment of structure and function. In this regard, the selection of typical species should be as robust and appropriate as possible.

The Guidelines for Article 17 reporting[1] (European Commission, 2023) provide some definitions and interpretations regarding typical species, such as the following:

- The assessment of typical species is part of the assessment of the structure and function parameter; however, a full assessment_of the conservation status (as for species listed in Annexes II, IV and V) of each typical species is not required.
- The selection of 'typical species' should reflect favourable structure and functions of the habitat type.
- Typical species should include species which are good indicators of favourable habitat quality, they should include species sensitive to changes in the condition of the habitat ('early warning indicator species').
- Typical species may be drawn from any species group and, although often most species reported were vascular plants, consideration should be given to also selecting lichens, mosses, fungi, and animals, including birds.
- The sum of sites and occurrences of each habitat type should support viable populations within the region being assessed of the typical species on a long-term basis for Structure and functions to be favourable.
- Given the ecological and geographical variability of the Annex I habitat across their range, even within a single biogeographical region, it is very unlikely that all typical species will be present in all examples of a given habitat type, particularly in large Member States (MSs). Indeed, even within one Member State different species may be present in different parts of the range of a habitat type or in different subtypes.
- Some species may be typical for several habitats (including non-Annex I habitats) and not dependent on a single Annex I habitat type.

All MSs have communicated a list of typical species for each habitat type[2], although usually they have not provided any justification or rationale for their selection. The variability of the selection of typical species by MSs seems to indicate that different interpretations are done on the concept of typical species. Mostly, plants are proposed as typical species (> 90% of the selected species). However, species from other taxonomic groups are also considered (e.g., lichens, insects, birds, mammals…)

It is advisable to select species from other taxonomic groups than plants, such as fungi, lichens, animals, micro-organisms. This is a challenge as plant data is more abundant and accessible. It can be useful to consider key functional groups for the selection of typical species, considering the habitat's ecology, the role of typical species as bioindicators (e.g. decomposers, trophic and symbiotic relationships, etc.) and their sensitivity to changes. Table 2 provides an illustrative list of species' groups that can be used as indicators to assess the condition of habitat type 8320.

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[1] Guidelines for Article 17 reporting: https://cdr.eionet.europa.eu/help/habitats_art17/Reporting2025/Final Guidelines Art. 17_2019-2024.pdf/

[2] The list (for all habitat types and MSs) is available at: https://cdr.eionet.europa.eu/help/habitatsart17

Table 2. Examples of typical species for habitat 8320 from different taxonomic groups

Species group	Ecological role: bio-indicator of	Sensitive to changes in quality
***Sterocaulon vesuvianum* (lichen)**	This lichen with a fruticolous thallus is a good indicator of the initial colonisation phase of recent volcanic soils in the Canary Islands (Beltrán & Dóniz, 2009)	Alteration or destruction of the volcanic surface by human activity.
***Racomitrium lanuginosum* (bryophyte)**	It can be dominant and forms thick moss carpets. This moss can inhibit the colonization of vascular plants, demonstrating a form of ecological succession where early colonists alter the habitat.	Sometimes it is restricting further succession (Björnsdóttir, 2015).
Bryophytes	Lava caves can serve as refuges for species like bryophytes, which show high diversity in such habitats	Refugia for various bryophytes species.
***Crocidura canariensis* (mammal)**	Endemic shrew of the Canary Islands, typical of semi-desert environments of lava with little or no vegetation (Beltrán & Dóniz, 2009).	Destruction of its habitat and predation, mainly by introduced foreign species such as cats, rats, etc.
***Apodemus sylvaticus, Mus domesticus* (mammals)**	Lava fields support several micrommal species	Several species identified after the analysis of long-eared owl (*Asio otus*) pellets from the Southeastern slope of Mt.Etna in Sicily, Italy (Siracusa et al., 2022).
***Gallotia galloti* (reptile)**	This lizard species is endemic to the Canary Islands and can be found in lava fields on Tenerife and La Palma, being well adapted to the harsh volcanic environment.	Disturbance by human activity and predation by domestic animals (cats, dogs).
***Podarcis siculus* (reptile)**	This species is common in various habitats, including lava fields on Mount Etna in Sicily. These adaptable lizards have been observed living on cooled lava flows and utilizing crevices in the volcanic rock for shelter.	Disturbance by human activity and predation by domestic animals (cats, dogs).
Invertebrates	Geothermally active lava fields, such as those in Krafla, Iceland, host diverse invertebrate communities, including nematodes, rotifers, tardigrades, and mites. Lava caves provide unique environments for specialized invertebrate species.	These organisms form complex trophic networks, indicating rich biodiversity even in extreme environments (Buda et al., 2018). Diversity influenced by both neutral and niche-based processes (Kristjánsson et al., 2024).
Vascular plants	Lava fields, such as those on La Palma, Canary Islands, show increasing plant diversity over time.	Initially dominated by native species, these areas eventually support a mix of endemic and alien species as succession progresses (Irl et al., 2019).
Xerophytic scrubs	Maintaining biodiversity	Enhancing ecological connectivity and support biodiversity.

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

According to the latest reporting period, habitat 8320 is present in Spain, Greece, Portugal, and Italy, with an overall conservation status of favourable (FV). However, Spain represents an exception, where the habitat's status has been assessed as unfavourable-inadequate (U1). The following analysis is based on the available methodologies from three countries: Spain, Greece, and Italy, since no monitoring information has been found for Portugal. The methodology developed for Greece by Dimopoulos et al. (2018) is not exclusive to habitat 8320 but applies to other rocky habitats as well. In contrast, the Spanish methodology by Beltrán and Dóniz (2009) was specifically developed for habitat 8320 in the Canary Islands. Additionally, Angelini et al. (2016) provide comprehensive guidelines for monitoring habitat 8320 in Italy. A summary of the variables, metrics and measurement methods presented in the consulted methodologies is presented in Table 3.

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

Abiotic variables

Regarding abiotic variables, the methodologies analysed predominantly include physical variables. Only one chemical variable has been proposed: the chemical and mineralogical composition of the rock material (Beltrán & Dóniz, 2009).

Beltrán and Dóniz (2009) establish the relationship between their proposed variables and habitat condition assessment, specifying which variables inform about the habitat context (referred to as descriptive variables in the present guidelines) and which variables inform about the current condition of the habitat. This distinction has been maintained in the summary of variables presented in Table 3, where D indicates descriptive variables that provide information on contextual factors.

The majority of physical variables have been presented in the methodology proposed by Beltrán and Dóniz (2009) for Spain. These are predominantly descriptive variables measuring contextual factors that do not directly provide information on habitat condition, such as magma type and age, lithology, substrate type, morphology, and climatic conditions. Where measurement methods are described, these typically rely on available information from relevant sources, including geological maps, published literature, meteorological stations, and similar resources.

The chemical composition of magmas and the chemical and mineralogical nature of rock substrates are included in one of the analysed methodologies (Beltrán & Dóniz, 2009). Laboratory analysis is indicated as the measurement method, but no threshold values are provided since these variables only provide contextual information.

Biotic variables

Biotic variables are the most frequently described components across the methodologies considered in this analysis. These primarily consist of compositional and structural attributes used to assess habitat condition, focusing on the presence and coverage of vegetation or specific species groups.

All three methodologies (Angelini et al., 2016; Beltrán & Dóniz, 2009; Dimopoulos et al., 2018) propose analysing vegetation by measuring the presence and coverage of typical, dominant, disturbance-indicator, and alien species. Angelini et al. (2016) specify the use of the Braun-Blanquet scale or percentage presence, whereas the other two methodologies rely on percentage cover. It should be noted that threshold values for these measures are provided by only one methodology (Beltrán & Dóniz, 2009).

The presence and coverage of nitrophilous and ruderal species are also proposed as indicators in two of the methodologies. Furthermore, Dimopoulos et al. (2018) include the presence of a cryptogam layer as a variable, though no specific methods or thresholds are provided for its assessment.

The methodology by Angelini et al. (2016) introduces additional variables related to habitat structure and function. The percentage of bare rock surface is used as a proxy for successional stage, with a mature stage defined by a maximum of 50% cover by vascular or bryophytic vegetation. This methodology also notes the presence of sulphobacteria and algae as indicative of specific environmental conditions, and emphasises the phytogeographic importance of endemic species, which often have low coverage but high local conservation value. However, no measurement methods or thresholds are indicated for these latter variables.

Several methodologies incorporate variables that assess anthropogenic pressure. Beltrán and Dóniz (2009) propose functional variables to measure habitat alteration from activities such as infrastructure development, extractive industries, and tourism. Similarly, Dimopoulos et al. (2018) recommends assessing substrate disturbances affecting natural dynamics, although this guidance is generic to all rocky habitats and lacks specific methods. Human interventions in the vicinity of the habitat, such as agricultural expansion or urbanisation, are also considered. For instance, an unfavourable conservation status is indicated by the presence of nitrophilous species or if more than 30% of the volcanic surface is altered by agricultural use, with measurement based on direct field observation and cartography.

Finally, it is noteworthy that none of the analysed methodologies explicitly include landscape-level variables. The alteration of the habitat due to external human activities, while addressed to some degree, could be more formally considered as a landscape factor.

Anemonium sp.
© Carlos Ibero.

Table 3. Variables included in the national methodologies analysed

Variable names	Metrics	Measurement methods	Thresholds	MS and references
1. Abiotic characteristics				
1.1 Physical characteristics				
Type and age of magma (D)	Type classes	Identification of the type of magma: tholeiitic, calc-alkaline and alkaline. Physical properties of magmas (density, rheology, etc.). Chronology of eruptions, which determine the floristic and physiognomic characteristics of the vegetation. Based on bibliography and documentation and field observation.	Not provided	ES: Beltrán & Dóniz, 2009
Type of substrate (D)	Type classes	Lava or pyroclasts. This variable provides further insight into controlling factors for vegetation distribution, but is not a determinant of vegetation condition.	Not provided	ES: Beltrán & Dóniz, 2009
Lithology (D)	Not provided	Identification of the physical properties of rocks. Identify cracks, joints, dips, floods, etc. Consultation of Geological Maps and field work to observe fissures and joints and measure length, orientations, dips and inclination.	Not provided	ES: Beltrán & Dóniz, 2009
Morphology (D)	Type classes	Relief forms (lava surfaces, cones, small ovens, cone-shaped craters, etc.), which help, in the absence of historical documents, to reconstruct the eruptive, geological and geomorphological history of recent volcanoes. Geological and geomorphological maps, geomorphological research work and photointerpretation.	Not provided	ES: Beltrán & Dóniz, 2009
Climatic conditions (D)	°C, mm, %	Temperatures, rainfall amount and distribution, humidity, etc. Measured for their influence of on the floral composition.	Not provided	ES Beltrán & Dóniz, 2009:
1.2 Chemical characteristics				
Chemical and mineralogical composition of substrate (D)	Not provided	Classification of magma into: ultrabasic, basic, intermediate and acidic. Laboratory analysis: chemical and mineralogical; X-rays, etc.	Not provided	ES: Beltrán & Dóniz, 2009

Variable names	Metrics	Measurement methods	Thresholds	MS and references
2. Biotic characteristics				
2. 1 Compositional and structural characteristics				
Vegetation cover and composition (compositional and structural)	scale of Braun-Blanquet or percentage coverage	Total vegetation cover, presence and cover of dominant species, disturbance indicator species, alien species, indicator species of ongoing dynamic phenomena, such as chamaephytes and nano-phanerophytes.	Not provided	IT: Angelini et al., 2016
Sulphobacteria and algae	Presence	Indicative of the pH, temperatures and chemical content of the gaseous emissions.	Not provided	IT: Angelini et al., 2016
Plant communities (compositional and structural)	Composition, % cover of vegetation	Vegetation inventories for description of the characteristics of the vegetation (composition, density and vegetation cover) in relation to the potential considering the bioclimatic strata	Favourable: the vegetation cover corresponds to the potential vegetation in each bioclimatic stratum and no nitrophilous and ruderal plants are observed. Unfavourable-inadequate: altered composition and presence of nitrophilous species represent 10%-25% of the floristic composition. Unfavourable-bad: highly altered composition and nitrophilous plants > 25% of the total inventory.	ES: Beltrán & Dóniz, 2009
Presence of cryptogam layer	Not provided	Not provided	Not provided	GR: Dimopoulos et al., 2018
Absence or low cover (<2%) of ruderals	%	Not provided	Favourable: <2%	GR: Dimopoulos et al., 2018

Variable names	Metrics	Measurement methods	Thresholds	MS and references
Percentage of bare rock surface	%	Evaluation of the rock surface exposed or encrusted with lichens, not covered by vascular or bryophytic vegetation. Analysis of the percentage ratio between initial-pioneer stage (little or no vegetation), mature stage (max. 50% vascular or bryophytic vegetation or bryophytic vegetation), senescent-stabilised stage (vascular or bryophytic vegetation with >50% coverage).	Not indicated	IT: Angelini et al., 2016
2.3 Functional characteristics				
Typical species reproducing (e.g. flowering and producing seed)	Not provided	Not provided	Not provided	GR: Dimopoulos et al., 2018
Alteration/degradation of the habitat by human activities (infrastructure, expansion of agricultural areas, quarries, urban discharges.	Degree of alteration and % of degraded area	On-site observation of alteration/ degradation of the habitat and the natural processes by occupation of the habitat or presence in its surrounding of human activity and infrastructure (roads, crops, quarries, presence of discharges) that have produced changes in morphology, vegetation and fauna (directly or indirectly). Direct observation during fieldwork and cartography to estimate the level of degradation of the habitat type: landforms, occurrence of nitrophilous and ruderal species, etc.	Favourable: when they have not been subject to any anthropic intervention Unfavourable-inadequate: when anthropic activity in the vicinity modifies the appearance of volcanic surfaces and partial aspects of the basic ecological processes, affecting in more than 30% of the total surface.	ES: Beltrán & Dóniz, 2009
Substrate with no significant disturbances of natural dynamics	Not provided	Not provided	Not provided	GR: Dimopoulos et al., 2018

D: indicates descriptive variables that provide information on contextual factors as presented in Beltrán & Dóniz, 2009.

2.2 Definition of ranges and thresholds to obtain condition indicators

The reviewed methodologies generally lack threshold values for most variables. Where thresholds are provided, the methods used to derive them are typically not specified.

Table 3 presents examples of such thresholds. For instance, one methodology proposes that a habitat is not in good condition if nitrophilous species constitute 10–25% of its floristic composition (Beltrán & Dóniz, 2009). Other states that ruderal species coverage must remain below 2% for a habitat to be considered in good condition (Dimopoulos et al., 2018). However, the latter provides no associated measurement methodology.

2.3 Aggregation at local scale

Only the methodology proposed by Beltrán and Dóniz (2009) presents a method for the aggregation of variables at local scale. A score is given to each of the variables measured: 2 when it is favourable, 1 when it is unfavourable-inadequate and 0 when it is unfavourable-bad. The overall status will be considered to be favourable if the sum of the points is equal to or greater than 75% of the total points available; unfavourable-inadequate if it is between >40% and <75% and unfavourable-bad when it is <40%.

2.4 Aggregation at biogeographical scale

The aggregation of local-scale assessments to determine habitat condition at the biogeographical level should adhere to the recommendations outlined in the Article 17 reporting guidelines for the 2013-2018 period. These guidelines specify that the status of the ‘structure and functions’ parameter is classified as ‘favourable’ if ≥90% of the assessed habitat area is in good condition. Conversely, the status is ‘unfavourable-bad’ if >25% of the area is not in good condition, and ‘unfavourable-inadequate’ for intermediate percentages (26-89%).

However, the correct application of this rule is contingent upon monitoring being conducted within a sufficiently representative area. This requires that the sampling strategy encompasses the habitat's full distribution and ecological diversity, incorporating a statistically significant number of samples. The methodologies reviewed in this analysis do not fully describe or document the procedures used to ensure this critical requirement is met.

2.5 Selection of localities

The selection of monitoring localities must be informed by a comprehensive understanding of the habitat's distribution and its associated subtypes.

For instance, Beltrán and Dóniz (2009) delineate five subtypes of habitat 8320 in the Canary Islands, classified according to orientation and climatic conditions, which in turn determine distinct floristic compositions and vegetation structures (see Table 4). The authors stipulate that locality selection should encompass the most representative areas for each subtype across the range of environmental conditions, with priority given to extensive, continuous surfaces.

A key consideration is the differential distribution of these subtypes. Subtype I has a widespread presence across nearly all islands. In contrast, the remaining subtypes occur at progressively higher altitudes and are correspondingly restricted to a smaller number of islands, culminating in Subtype V, which is endemic to Tenerife.

Table 4. Habitat 8320 subtypes of the Canary Islands

Adapted from Beltrán and Dóniz, (2009).

Subtypes		Islands
I.	Warm climate with annual rainfall less below 350 l/m^2	Lanzarote, Fuerteventura, Gran Canaria, Tenerife, La Palma, El Hierro
II.	Warm-temperate climate with annual rainfall between 200 and 600 l/m^2	Lanzarote, Gran Canaria, Tenerife, La Palma, El Hierro
III.	Temperate climate with annual rainfall between 300 and 1100 l/m^2, depending on the orientation of the island and the altitude.	Gran Canaria, Tenerife, El Hierro
IV.	Cool climate environment with annual rainfall greater than 700 l/m^2	Tenerife, La Palma
V.	Cold climate environment with annual rainfall between 400 and 800 l/m^2 Tenerife	Tenerife

The monitoring programme must account for factors posing a risk to the habitat's conservation. Consequently, the methodology advises considering the relationship between the identified subtypes and the anthropogenic pressures affecting them. This includes, for example, volcanic areas situated within zones of intensive agriculture or those bordering urban developments, which are consequently under significant threat of degradation or loss.

A total of 20 localities were selected for Subtype I, 13 for Subtype II, 4 for Subtype III, 8 for Subtype IV, and 4 for Subtype V. These localities are situated both inside and outside the Natura 2000 network, with a higher proportion located within it, reflecting the habitat's extensive coverage in Special Areas of Conservation.

Angelini et al. (2016) note that the existing monitoring network managed by the National Institute of Geophysics and Volcanology tracks seismic activity, ground deformations, and gas emissions from the soil and fumaroles of all active Italian volcanoes: Vesuvius, Etna, Stromboli, Vulcano, Campi Flegrei, and Ischia. However, the methodology does not specify the number of monitoring locations in the vicinity of these volcanoes.

In Greece, monitoring locations were selected based on sampling sites established during the IDH-TACI project (1999–2001) and the need to assess the conservation status of habitat types in areas with insufficient existing data (Dimopoulos et al., 2018).

2.6 General monitoring and sampling methods

No monitoring protocols are included in the methodology available for Greece (Dimopoulos et al., 2018) specific for fields of lava and natural excavations.

The methodology available for Spain does not describe detailed sampling protocols but does indicate sampling frequencies of 3 to 4 years for the proposed variables to assess vegetation composition, considering the dominant semi-arid climate that determines a slow rate of plant colonisation (Beltrán & Dóniz, 2009). Regarding variables related to habitat alteration by human-related pressures, considering the extraordinary population increase experienced by the Canary Islands, these should be monitored annually, including consultation of local and island plans which provide information on urban growth or the expansion of new agricultural areas.

The methodology available from Italy (Angelini et al., 2016) proposes vegetation monitoring to be repeated over time within permanent plots in order to detect changes in a timely manner, with a recommended frequency of 3 years. An optimal sampling period between March and August (depending on the altitude of the surveyed station) is indicated. A minimum homogeneous survey area of 5-20 dm^2 is proposed for plant communities of summit areas, 16-25 m^2 for phanerogamic vegetation, and up to 100 dm^2 for fumarole bryocoenoses. An optimal minimum number of samplings is suggested, with at least one sampling per unit of homogeneous surface: one sampling every 1,000 m^2 (0.1 ha) for bryophyte and lichen vegetation, and one sampling every 2-10 ha (based on the extension and local homogeneity) for phanerogamic vegetation.

If deemed necessary, it is possible to acquire data from existing monitoring networks in Italy, where the National Institute of Geophysics and Volcanology maintains regular monitoring of all active volcanoes in Italy (Vesuvius, Etna, Stromboli, Vulcano, Campi Flegrei, and Ischia) through a widespread seismic network and high-technology instrumentation. This monitoring encompasses seismic activity, ground deformations, and gas emissions from the ground and fumaroles. The data produced are analysed by automatic systems and controlled and interpreted by researchers from different sectors.

2.7 Other relevant methodologies

Several studies analysing colonisation patterns and succession on volcanic surfaces offer relevant insights for monitoring this habitat type.

A study by Karadimou et al. (2018) on the Nea Kameni volcanic island (Santorini Archipelago, Greece) investigated post-eruption plant community evolution. The research focused on three key aspects: temporal changes in taxonomic and functional diversity (both alpha and beta), shifts in 26 specific plant traits throughout the succession process, and the mechanisms driving species assembly and their temporal variation. The analysis incorporated data from five botanical surveys conducted between 1911 and 2011. Changes in community structure were assessed using 26 functional traits—including growth form, Ellenberg indicator values, seed production and weight, flower size and sex, pollination type, and dispersal mode. These traits were selected for their utility in distinguishing between early and late colonisers, encompassing factors such as lifespan, growth patterns, ecological preferences, and reproductive and dispersal strategies. The study highlights legacy effects in succession, where plants survive disturbance via underground structures; this was evidenced by the high proportion of perennial species present in the community immediately after the eruption.

The functional traits applied in this study, such as seed production and growth form, could be integrated into the monitoring framework for Habitat 8320 due to their relevance for explaining succession stages and plant community assembly.

A further study by Elias et al. (2004) investigated the influence of substrate age and soil characteristics on primary succession on the island of Terceira (Azores). The researchers selected three comparable lava domes of differing ages. At these sites, a comprehensive dataset was collected, detailing floristic composition, vegetation bio-area (the area occupied by plant species within transects), plant community structure, plant population demographics, and soil properties. The soil analysis included organic matter (%), total nitrogen (%), phosphorus (ppm), potassium (ppm), pH, and carbon-to-nitrogen ratio.

The study identified clear trends in soil development across the chronosequence. With increasing dome age, the percentage of organic matter and nutrient concentrations rose, while the carbon-to-nitrogen ratio and soil acidity decreased. The research also demonstrated that successional rates varied across topographic positions on the domes. Succession progressed more rapidly in areas with conditions more favourable to plant establishment and soil development, such as foot slopes (benefiting from proximity to surviving vegetation) and summits (where fissures facilitated plant growth). In contrast, dome slopes exhibited slower successional rates, attributed to lower initial colonisation, reduced secondary dispersal, and less favourable conditions for pedogenesis. These findings emphasise the critical role of local topography and environmental heterogeneity in governing the trajectory and pace of succession on volcanic landscapes.

Regarding monitoring techniques, there has been an increase on the use of remote sensing on monitoring of volcanic areas and their elements.

Gałaś et al. (2023) focused on reconstructing the volcanic history of the Valley of the Volcanoes, a key area within the Quaternary Andahua Group, where some eruption centres have exhibited renewed activity after more than 500,000 years. The research employed satellite data and remote sensing methods—including SRTM 30 m Digital Elevation Models (DEM), Landsat 7 and 8, and ASTER imagery (with an emphasis on channels 4, 3, and 2)—to analyse terrain and volcanic features. Fieldwork was conducted to verify and refine the satellite data, utilising Structure-from-Motion (SfM) techniques to generate high-resolution 3D models of selected geoforms. This integrated methodology facilitated the production of Red Relief Image Maps, Topographic Position Index maps, and Normalized Difference Vegetation Index (NDVI) maps.

The study further investigated the correlation between vegetation coverage on lava surfaces and its potential for determining relative flow ages. Differences in petrography and geochemical characteristics were analysed to identify patterns of magma differentiation related to eruption timing and location. Remote sensing techniques were critical for delineating the extent of individual volcanic product generations and tracing lava flow paths from vents to flow fronts, thereby complementing field observations. A key objective was to establish a chronological sequence and provide a volumetric assessment of individual eruptions.

Guinn et al. (2024) applied remote sensing techniques to measure Normalized Difference Vegetation Index (NDVI) variations and assess their potential for monitoring volcanic CO_2 emissions. The study analysed NDVI signals from Landsat 8, MODIS, Sentinel-2, and VIIRS platforms alongside soil CO_2 flux data from five stations on Mt. Etna, collected between 2011 and 2018. NDVI values were calibrated across the different sensors to account for variations in their spectral and technical characteristics. By calculating the second derivatives of both the NDVI and soil CO_2 flux data, the researchers identified periods of increasing and decreasing degassing, which reflected magma migration from an intermediate to a shallow storage chamber. This analysis detected 16 distinct magma recharge events between 2017 and 2018, evident in both the NDVI and CO_2 signals.

A similar technique was employed by Tolometti et al. (2020) to assess lava properties at the Craters of the Moon (COTM) National Monument and Preserve in Idaho, USA. In this application, variations in surface roughness across the lava field provide insights into temporal and spatial changes in lava properties and emplacement processes. The study correlated geochemical and petrographic analyses of different lava flow morphologies with airborne radar data. The findings demonstrated that radar data can differentiate surface roughness at COTM, distinguishing smoother, primitive lava flows with lower SiO_2 and alkali content from rougher, evolved flows with higher concentrations of these elements.

2.8 Conclusions

The three consulted methodologies demonstrate a high degree of similarity. Collectively, the variables they encompass cover key characteristics of Habitat 8320, as detailed in Table 1. These include climatic elements, lava type, substrate composition, and the presence and coverage of various species. However, significant gaps remain.

The consulted methodologies do not measure certain taxonomic groups like mosses or lichens and only one methodology considers the presence of other organism characteristic of fumarolic environments, such as sulphobacteria and algae (Angelini et al., 2016). The focus is exclusively on plant species, despite the potential presence of characteristic fauna, such as certain invertebrates, lizards, and small mammals.

Only three national methodologies for the assessment and monitoring of Habitat 8320 were identified within the EU. One of these references (Dimopoulos et al., 2018) is not specific to this habitat, as it also covers other rocky habitats. Consequently, it is unclear which of its variables are applicable for monitoring 8320. Furthermore, the methodologies do not systematically incorporate data from official monitoring networks, such as those operated by the National Institute of Geophysics and Volcanology.

One methodology includes the measurement of physical and chemical substrate characteristics, as well as certain climate variables. While these are essential for understanding the environmental context and colonisation processes, they do not directly determine whether the habitat is in good condition.

All three methodologies focus on assessing vegetation composition, the patterns of plant community colonisation, and the habitat's degradation or alteration by human activities and associated pressures. Consequently, the condition variables are linked to these two main elements: the vegetation itself and the detection of signs of degradation. The latter includes the presence of nitrophilous, ruderal, and alien species, as well as direct disturbance from human activity and infrastructure.

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

3.1 Selection of condition variables, metrics and measurement methods

Based on the key characteristics identified for this habitat type and on the analysis of the main variables used to assess the habitat condition in the national methodologies available, as described in the previous chapter, a selection of variables is proposed in Table 5. This selection aims to establish a minimum common set of variables, encompassing abiotic (physical and chemical), biotic (composition, structure, and function), and landscape variables, including their measurement methods.

A proposed list of essential, optional, specific condition variables for habitat 8320 is exhibited in Table 5, including metrics and general measurement procedures. In addition, a number of **descriptive variables** are also proposed, which inform on the context of the habitat and can be relevant to understand the processes that can influence their ecological status, but do not directly inform of such condition (e.g. lithology, geo-forms). **Essential** variables correspond to characteristics that are essential for the habitat (e.g., coverage of vascular plants), describe the distinctness of the habitat (e.g., characteristic species) or its condition (e.g., typical and alien species, coverage). **Recommended** variables correspond to common variables which are relevant but that can be neglected to be measured in some contexts.

The proposed metrics are intended to be easily, but reliably obtained, most of them at plot level.

Whilst **descriptive variables** do not directly indicate current habitat quality, they are indispensable for interpreting ecological patterns, understanding habitat constraints, and structuring effective monitoring protocols.

The climatic context is defined through temperature and rainfall data that can be obtained from meteorological stations. Average temperatures establish the thermal regime that influences primary productivity rates and determines which species can successfully establish within volcanic substrates. Rainfall amount and distribution patterns control moisture availability, directly affecting succession rates, chemical weathering processes, and vegetation development patterns across different volcanic terrain types.

Geological characteristics represent fundamental controls on habitat development. The type of lava and pyroclastic materials, which can be determined through geological maps, LiDAR, and Ground Penetrating Radar analysis (Gómez-Ortiz et al., 2006), dictates critical substrate properties including permeability, nutrient availability, and physical stability for colonising organisms. These geological parameters vary significantly between volcanic systems and directly influence which ecological communities can establish and persist.

Topographic variables derived from high-resolution elevation data supply critical spatial context for lava field habitats. Altitude influences climatic factors such as temperature and precipitation gradients, shaping species distributions along elevation zones (Poli Marchese, 2021). Aspect governs solar radiation and wind exposure, creating microclimatic niches that determine local habitat suitability. Detailed analysis of Digital Elevation Models-derived parameters—slope, aspect, curvature, and flow accumulation—characterises surface morphology, drainage patterns, microhabitat diversity, and accessibility for biological colonisation. Such analysis also elucidates lava flow morphology by identifying sub-metre-scale features and revealing interactions between flow pathways and underlying terrain

(Richardson & Karlstrom, 2019). Moreover, monitoring topographic changes enables quantification of volumetric gains and losses during eruptions, offering insights into eruption dynamics and lava extrusion rates (Dirscherl & Rossi, 2018; Macfarlane et al., 2013).

Advanced technologies including UAVs, LiDAR, and satellite imagery provide high-resolution datasets that enhance habitat characterisation accuracy within challenging volcanic terrain, enabling comprehensive documentation of lava field morphology, vegetation colonisation patterns, and habitat structural complexity (De Beni et al., 2019; Corradino et al., 2019; Favalli et al., 2018). These platforms overcome accessibility constraints typical of rugged lava field environments, supporting systematic habitat assessment and temporal monitoring across extensive volcanic landscapes relevant to ecological monitoring objectives.

Regarding the proposal of **essential variables**, substrate chemistry represents a critical factor influencing ecological processes within volcanic habitats. Laboratory analysis of rock samples can be supplemented by literature data on magma composition in order to determine and classify the substrate into ultrabasic, basic, intermediate and acidic. Substrate nature determines nutrient availability, substrate stability, and chemical constraints on species establishment. The chemical weathering products also influences soil development and create spatial gradients in habitat suitability that directly affect colonisation success.

The compositional assessment focuses on the presence and abundance of characteristic species across major taxonomic groups. Visual field surveys are used to document mosses, lichens, and vascular plants; these organisms serve as indicators of the successional stage, habitat typicity, and colonisation potential. Fauna assessment, conducted through targeted observations of invertebrates, reptiles, birds, and mammals, provides insights into trophic complexity and functional diversity within the volcanic ecosystem.

Regarding structural variables, the visual estimation of vegetation and bare substrate coverage provides fundamental metrics for assessing colonisation success and determining successional status. A detailed assessment of vegetation and cryptogram layer coverage by taxonomic group (lichens, mosses, and vascular plants) is proposed as an essential variable since it reveals patterns in community composition and habitat quality gradients across the volcanic terrain.

At the landscape scale, assessment focuses on evaluating indirect pressures by analysing the expansion of human activities and infrastructure development. The integration of aerial photography, field surveys, and GIS mapping is used to document pressures such as urbanisation and agricultural expansion, thereby quantifying land-use changes that affect habitat integrity and ecological function across broader spatial scales.

The direct observation of species reproduction (flowering, seed production) during appropriate phenological periods is proposed as a **recommended variable** that indicates population viability and regeneration potential. These functional assessments provide early warning indicators of population decline or ecological stress.

Table 5. Proposal of variables for habitat group 8320 – Fields of lava and natural excavations

Characteristics	Variables	Metrics	App	Standardised measurement procedures	Considerations relating to methodologies
1. Abiotic characteristics					
1.1 Physical state characteristics					
Climatic conditions	Temperature (average)	ºC	D	Data obtained from meteorological station	
	Rainfall amount and distribution	mm or %	D	Data obtained from meteorological station	
Geomorphological characteristics	Type of lava and/or pyroclastic material	Classes	D	Geological maps, LiDAR, GPR	
Topographic characteristics	Altitude	m	D	Data from maps and documentation, LiDAR	
	Orientation	%	D	Data from maps and documentation, LiDAR	
1.2 Chemical state characteristics					
Chemical composition of the substrate	Chemical and mineralogical composition of substrate	Type of magma	E	Based on data available or though laboratory analysis	Chemical and mineralogical composition of substrate. Type of magma: ultrabasic, basic, intermediate and acidic,
2. Biotic characteristics					
2.1 Compositional state characteristics					
Vegetal community composition	Presence of characteristic species: mosses, lichens	Presence, numbers of species	E	Visual assessment in the field	Based on local or regional reference lists.
	Presence of characteristic species: vascular plants	Presence, numbers of species	E	Visual assessment in the field	Based on local or regional reference lists.

Characteristics	Variables	Metrics	App	Standardised measurement procedures	Considerations relating to methodologies
2. Biotic characteristics					
2.1 Compositional state characteristics					
Faunal community composition	Presence of characteristic fauna: invertebrates, reptiles, birds, mammals	Presence, numbers of species	E	Visual assessment in the field. Traps for invertebrate fauna or acoustic monitoring for birds.	Based on local or regional reference lists.
Disturbance indicator species	Presence of: nitrophilous and invasive alien species	Presence, numbers of species	E	Visual assessment in the field.	Presence of species indicating alteration of the habitat by human activity and related pressures. Based on local or regional reference lists.
2.2 Structural state characteristics					
Community occupation patterns	Cover of vegetation and bare substrate	% or ratio vegetation/bare substrate	E	Visual assessment in the field or aerial photography/satellite imagery.	
	Cover of vegetation and cryptograms by taxonomic group	% cover per taxonomic group	R	Visual estimation in the field.	Coverage of taxonomic groups measured by the compositional variables: mosses, lichens, vascular plants. Based on local or regional reference lists
	Cover of: nitrophilous and invasive alien species	%	E	Visual assessment in the field or aerial photography/satellite imagery.	
2.3 Functional state characteristics					
Dynamic and natural processes	Characteristic species reproducing	%	R	Visual assessment in the field.	Vascular plant species measured by the compositional variables flowering and producing seed. Based on local or regional reference lists
3. Landscape characteristics					
Landscape metrics	Patch size and inter-patch distances	m^2 or ha (area) and m or km (distance)	E	Aerial photography, GIS mapping.	Estimation of total area of patch size.

Characteristics	Variables	Metrics	App	Standardised measurement procedures	Considerations relating to methodologies
3. Landscape characteristics					
Anthropic impact	Expansion of human activities and infrastructure	Presence and % coverage	E	Aerial photography, field observation, GIS mapping.	Human activities and infrastructure in the surrounding areas that indirectly affect the habitat (agriculture, quarries, urban discharges, litter etc.)

App.: Application. D: Descriptive. E: Essential. R: Recommended.

3.2 Definition of ranges and thresholds to obtain condition indicators

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

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

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

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

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

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

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

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

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

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

Absolute biophysical boundaries

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

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

Comparison to empirical cases considered to be in good condition

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

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

Comparison to cases with a natural disturbance regime

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

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

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

Modelling the relationships between variables and condition

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

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

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

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

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

Statistical assessments

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

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

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

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

Expert judgement

Setting of reference values and thresholds based on expert judgement is common practice, particularly where other sources of information are lacking – for instance, in certain non-abundant habitats where experts have developed empirical knowledge of habitat condition. However, this approach is often criticised for its limited transparency, and the level of expertise may be insufficient in some cases. For this reason, it is sometimes considered a last-resort option for many variables.

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

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

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

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

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

This classification of variable values – whether quantitative or categorical – into condition categories (e.g., good 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 is likely to be measured in a different unit. Owing to the different metrics and magnitudes used for the variables that characterise habitats, the values obtained from their measurement require some form of standardisation – e.g., through re-scaling – in order to build indicators that combine multiple variables. These values are normalised using reference levels and reference conditions, allowing comparison across variables. Measurement values are thus scaled in relation to their reference levels, thereby normalised to a common scale and aligned 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, covering the full range of habitat conditions – from degraded to high-quality examples.

3.3 Aggregation methods at the local scale

Ecological assessments require the integration of physical, chemical, and biological quality elements. The choice of aggregation method for combining these partial assessments into an overall evaluation has been widely discussed within the scientific community, as it can significantly influence the final outcome. Various approaches can be used to integrate the values of measured variables into an overall index reflecting the condition of habitat types at the local scale (e.g., monitoring plot, station, or site).

Applying appropriate aggregation approaches is essential for categorising condition at the local scale as good or not good, since the proportions of habitat type area in good/not good condition is the key information needed for evaluating the conservation status of structure and functions at the biogeographical level.

3.3.1 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 the minimum aggregation, the aggregated value is calculated as the minimum of the values of the measured variables.

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

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

Conditional rules

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

Simple additive methods and averaging approaches

Simple additive methods calculate an aggregated value as the sum of the n values (vi) of the variables.

Averaging approaches are among the most commonly used methods for aggregating indicators. These include straightforward calculations such as the arithmetic mean, weighted average, median, or combinations thereof, to produce an overall assessment value.

Weighting

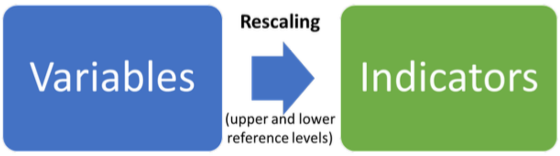
Differential weighting of indicators may be applied when calculating sums, means, or medians. The choice of weighting system should reflect the relative importance of each indicator in determining the overall condition of the ecosystem. Ideally, the approach should be supported by a clear scientific rationale and informed by input from ecologists with expertise in the relevant ecosystem types.

However, a robust basis for assigning weights is not always available. In such cases, weighting often relies on expert judgment, which can be subjective, as expert opinions may differ considerably.

Normalization of variables values (rescaling)

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

Figure 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 in order to obtain comparable results. The main steps for aggregation are described below.

Step 1 – Normalisation of the variables

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

Step 2 – Aggregation of normalised variables

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

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

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

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

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

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.

Limit between good/not good condition

3.4 Aggregation at biogeographical scale

The aggregation of condition indices obtained at the local scale is essential for assessing habitat conditions at a broad habitat biogeographical region level. According to the Art. 17 reporting guidelines (European Commission, 2023), specific rules have been established to determine the overall habitat condition based on local assessments:

- If **90%** of the habitat area is considered in **'good' condition**, then the status of the **'structure and functions'** parameter is classified as **'favourable'**.
- Conversely, if more than **25%** of the habitat area is reported as **'not in good condition'**, then the **'structure and functions'** parameter is deemed **'unfavourable-bad'**.

The application of this rule requires that the assessment covers a sufficient representation of the habitat, so that the results properly reflect the conditions in the total habitat area. The selection of localities and the number of sampling pots/stations should be carried out to ensure that they are statistically representative of the whole habitat distribution.

3.5 General monitoring and sampling methods

At the biogeographical scale, sampling sites should be systematically distributed across the full extent of lava fields and natural excavations to capture the spatial variability in habitat and ecological conditions. It is vital to ensure that monitoring captures the diversity and dynamics of this habitat type throughout its range.

Within the Natura 2000 network, selection of representative monitoring sites must align with conservation priorities. Efforts should concentrate on areas critical for the preservation of key habitat features, thereby supporting compliance with European conservation objectives. By doing so, monitoring can demonstrate progress towards favourable conservation status and detect any threats or declines.

At the site level, multiple sampling points should be established within individual locations to record localised habitat variation and species diversity. This approach enhances the capacity to identify changes at fine spatial scales, which might otherwise be overlooked in broader assessments.

The size and number of monitoring sites require careful consideration. In large lava fields with relatively uniform environmental conditions, the entire area may be considered as a single monitoring locality. For areas with fewer or more fragmented lava fields, each site should be subject to regular and repeated monitoring to ensure meaningful data collection. Where lava fields are numerous, it is recommended to select a balanced number of sites that reflect a diversity of situations, ecological zones, and habitat conditions.

The recommendations proposed in this section have been drawn from literature and the methodologies reviewed in Section 2.6.

The proposed monitoring period is six years, chosen to align with the Article 17 reporting cycle. This duration is consistent with the frequency recommended in existing methodologies from Member States (typically 3–4 years, as cited in Angelini et al., 2016 and Beltrán & Dóniz, 2009). Consequently, this six-year window allows for the target variable to be monitored at least twice within a single reporting period.

Physical-descriptive variables should be measured once at the commencement of each monitoring period. Climatic variables, by contrast, require annual measurement to accurately track the evolution of habitat conditions.

In regards to vegetation surveys, a combination of field observations with aerial photography and remote sensing analysis is recommended. The sampling frequency should be set accordingly to the rate of plant colonisation and development characteristic of each region. Angelini et al., (2016) establishes a 3-year period and Beltrán and Dóniz (2009) a 3 to 4-year period for semi-arid climates. In contrast, indicators of habitat alteration linked to anthropogenic pressures require more frequent assessment and should be measured annually. They should be complemented by local urban and agricultural development plans, thus providing essential context and additional data on emerging habitat threats.

Vegetation monitoring can be conducted within permanent plots with all vascular plants, bryophytes and lichens being recorded. The floristic survey conducted in lava fields in the La Palma (Canary Islands, Spain) by Irl et al., (2019) used 4 m^2 plots at different elevation intervals of 100 m, ranging from a set range of meters above sea level and placing three replicate plots at each elevational interval on a given lava flow. A similar sampling scheme can be applied with the sampling plot and the representation of the elevation gradient being adapted to each region characteristics. Following Angelini et al., (2016), homogeneous survey areas should be defined inside each location according to the targeted group characteristics, the habitat extent and the local homogeneity. Its recommendations include a minimum homogeneous survey area of 5–20 dm^2 for plant communities of summit areas, of 16–25 m^2 for phanerogamic vegetation, and up to 100 dm^2 for fumarole bryocoenoses.

Fauna monitoring techniques will depend on the targeted species but direct observation and point count from the sampling plots is recommended as a basic and easy solution. For invertebrate species, sampling traps and bulk samples can be used.

The recommended sampling season is from March to April, depending on the altitude (Angelini et al., 2016; Irl et al., 2019). The sampling season should fall between the months where vegetation is flowering which sometimes might not coincide with the season where the different targeted fauna is more active.

Where existing monitoring networks are active, such as those maintained by the National Institute of Geophysics and Volcanology in Italy, data from seismic, geophysical, and gas emission monitoring can complement habitat monitoring efforts. These networks routinely collect and analyse information using a combination of automatic detection and expert interpretation, providing valuable contextual data for ecological assessments.

3.6 Selection 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 for each habitat type at the biogeographical scale.

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

- Ecological variability: Localities must represent the full range of ecological diversity and variability within the habitat type. Selection should include different ecotypes or subtypes, successional stages, and reflect key environmental gradients such as altitude, soil type, moisture levels, geomorphological features, and topography.
- Spatial coverage: Adequate spatial coverage is essential to capture habitat heterogeneity. Localities should be selected across the full geographical range of the habitat type within the region, ensuring they are well distributed and represent a significant proportion of the habitat's total occupied area.
- Degree of conservation and exposure to pressures and threats: The selection of monitoring localities should include areas with varying degrees of conservation and degradation, in order to capture the full range of habitat condition across its distribution. This includes both well-conserved areas with minimal human impact, and areas affected by degradation and subject to different pressures. To reflect the diversity of pressures acting on the habitat, localities should span a range of intensity levels – from low to high – and account for different sources of disturbance, such as urbanisation, agriculture, and climate change.

- Presence inside and outside Natura 2000 sites: The assessment and monitoring of habitat conservation status must be carried out both inside and outside Natura 2000 sites. This requires selecting localities – and an appropriate number of plots – that reflect the proportion to the habitat's distribution within and outside the Natura 2000 network.
- Habitat fragmentation at landscape scale: Localities should be selected based on landscape metrics such as patch size and connectivity. Including both isolated and well-connected sites allow for the assessment of fragmentation effects on habitat condition. Understanding these patterns is essential for developing strategies to mitigate the negative impacts of habitat fragmentation.
- Lack of information: Including areas where data are lacking contributes to building a more comprehensive dataset. Selecting localities in historically under-sampled regions ensures a more balanced and complete understanding of habitat condition across its range. This helps to address data gaps and supports more informed conservation planning.
- Accessibility and practicality: Monitoring localities should be accessible for regular field visits, taking into account logistical factors such as distance from roads and ease of access. Practical considerations also include the safety of field personnel and the feasibility of transporting equipment to and from the site.
- Historical data and existing monitoring sites: Making use of existing monitoring sites with historical data can strengthen the understanding of long-term trends and changes in habitat condition. Such sites provide valuable baselines for comparison and support more robust trend analyses over time.

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

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

Considering the heterogeneity of habitat types, it is highly recommended to consult a sampling statistician when determining sample size – that is, the minimum number of plots required to ensure representativity and statistical significance. Some key elements for ensuring proper representation of habitat condition in the sample are summarised below:

Sample size and distribution

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

Sampling design

- Within each sampling area or locality, multiple plots are established to collect detailed data on vegetation, soil, and other ecological indicators. The number and distribution of plots depend on the size of the habitat patch and its internal variability.

- Sampling areas (e.g., plots, transects) should be laid out with consideration of the main ecological gradients, such as altitude, moisture, and exposure to sea influence.

Replication and randomisation

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

3.7 Other relevant technologies

Multispectral satellite data, such as that from Sentinel 2 and Landsat, provides comprehensive mapping that can be utilised to identify variations in habitat across lava fields, distinguishing areas of ecological significance and monitoring their development over time (Corradino et al., 2019, Stoyanov; 2023). UAVs, equipped with high resolution cameras and Structure from Motion photogrammetry, support detailed digital elevation models and orthophotos, which are invaluable for assessing habitat structure, vegetation patterns, and accessibility in both safe and inaccessible areas (De Beni et al., 2019; Favalli et al., 2018).

While automated detection systems that analyse thermal imagery have primarily been developed for eruptive activity and hazard assessment, the data can also contribute to habitat monitoring by identifying zones of recent change or disturbance if adapted to ecological monitoring objectives (Calvari & Nunnari, 2022). Integrating data from ground-based, aerial, and satellite sources enables a more comprehensive understanding of the ecological diversity found within lava landscapes. This integration supports efforts to estimate changes in habitat extent and condition, as well as the distribution of key habitat features, which are fundamental to conservation management. Machine learning techniques applied to satellite imagery may further enhance the mapping of habitat types, stages of ecological succession, and species distribution, improving ecological monitoring and predictive modelling (Corradino et al., 2019).

Future monitoring directions should prioritise the development of systems and modelling tools that track habitat structure, ecological function, and biodiversity across lava fields, facilitating timely response to environmental changes and the design of targeted conservation measures. This shift in emphasis, from risk assessment towards ecological monitoring, supports the effective management and preservation of lava field habitats and their unique biological communities.

4. Guidelines for evaluating fragmentation at appropriate scales

European volcanic fields exhibit varied fragmentation patterns depending on their geological age, eruptive history, and degree of human intervention. Natural fragmentation is driven by the primary volcanic topography, including the formation of individual lava flows, scree slopes, and volcanic cones, which create a complex mosaic of isolated substrates of varying ages and stability. Anthropogenic fragmentation significantly exacerbates this natural patchiness. The development of linear infrastructure (e.g., roads, pipelines), urban expansion, quarrying, and conversion to agricultural land dissect continuous lava fields into smaller, more isolated patches.

A practical approach for evaluating fragmentation in lava fields and natural excavations involves assessing key landscape metrics. These include measuring patch size to determine the area of suitable habitat, and calculating inter-patch distances. Remote sensing and GIS technologies play a crucial role in this process. Satellite imagery, aerial photography, and GIS mapping allow for the systematic identification of habitat patches, evaluation of their size, shape, and proximity, and consistent tracking of landscape changes over time (Foody, 2023).

The analysis should also account for the presence of fragmenting infrastructure, such as roads, agricultural land, and urban developments, to evaluate the degree of patch isolation and the barrier effects imposed by these structures.

Box 2. Key factors contributing to fragmentation

- **Natural disturbances**: Volcanic activity, erosion, and natural disasters can alter the landscape, leading to fragmentation of lava fields and natural excavations. Monitoring the impacts of such disturbances is crucial for understanding habitat persistence.
- **Hydrological changes**: Altered water flow and drainage patterns can influence the spatial distribution of habitats, affecting their fragmentation. Monitoring hydrological systems near lava fields is essential to assess these impacts.
- **Geological factors**: The underlying geology and topography of the area can significantly influence habitat distribution. Areas with steep slopes or unstable substrates may be more prone to fragmentation.
- **Human activity**: Anthropogenic factors such as land development, agriculture, and tourism can exacerbate fragmentation by altering natural landscapes. Assessing the impact of human activities is vital for effective habitat management.

5. Next steps to address future needs

These guidelines recommend standard methods for assessing and monitoring lava fields habitat condition with the goal of promoting harmonised procedures across the EU Member States. 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 mire habitats.

To implement these guidelines, the following next steps are suggested:

- **Test the proposed set of variables** with agreed measurement procedures and monitoring methods. Use common protocols for sampling, while considering the particularities of different habitats and the existing contextual factors at local and country level; this testing would be useful to identify gaps of knowledge, flaws of applicability and robustness and reliability of results. The evaluation should provide recommendations to be further integrated in the harmonised procedure, as needed.
- Develop further, test and standardise the methods for the establishment **of reference values and thresholds** to determine good condition. Defining ecological thresholds based on proper habitat characterisation is essential. These thresholds will indicate the health and quality of these rocky habitats, aiding in the monitoring of changes over time. They will also facilitate the assessment of impacts of climate change, human activities, and invasive species, providing critical insight for conservation efforts.
- Develop further, test and standardise the methods for the **aggregation of results** obtained from all the variables measured at the local scale and for each biogeographical region.
- **Develop further and test the criteria for the selection of monitoring localities and sampling design** to ensure a sufficiently representative sample that allows for proper implementation of the aggregation of results at the biogeographical region level.
- **Promote harmonised methods for the use of typical species**: Typical species provide a practical way to evaluate habitat status, reflecting specific ecological conditions. Clear criteria should be defined for selecting these species, along with the methodologies to assess their status and integrate the results into overall condition assessment for each habitat.

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

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KH-01-25-201-EN-N

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