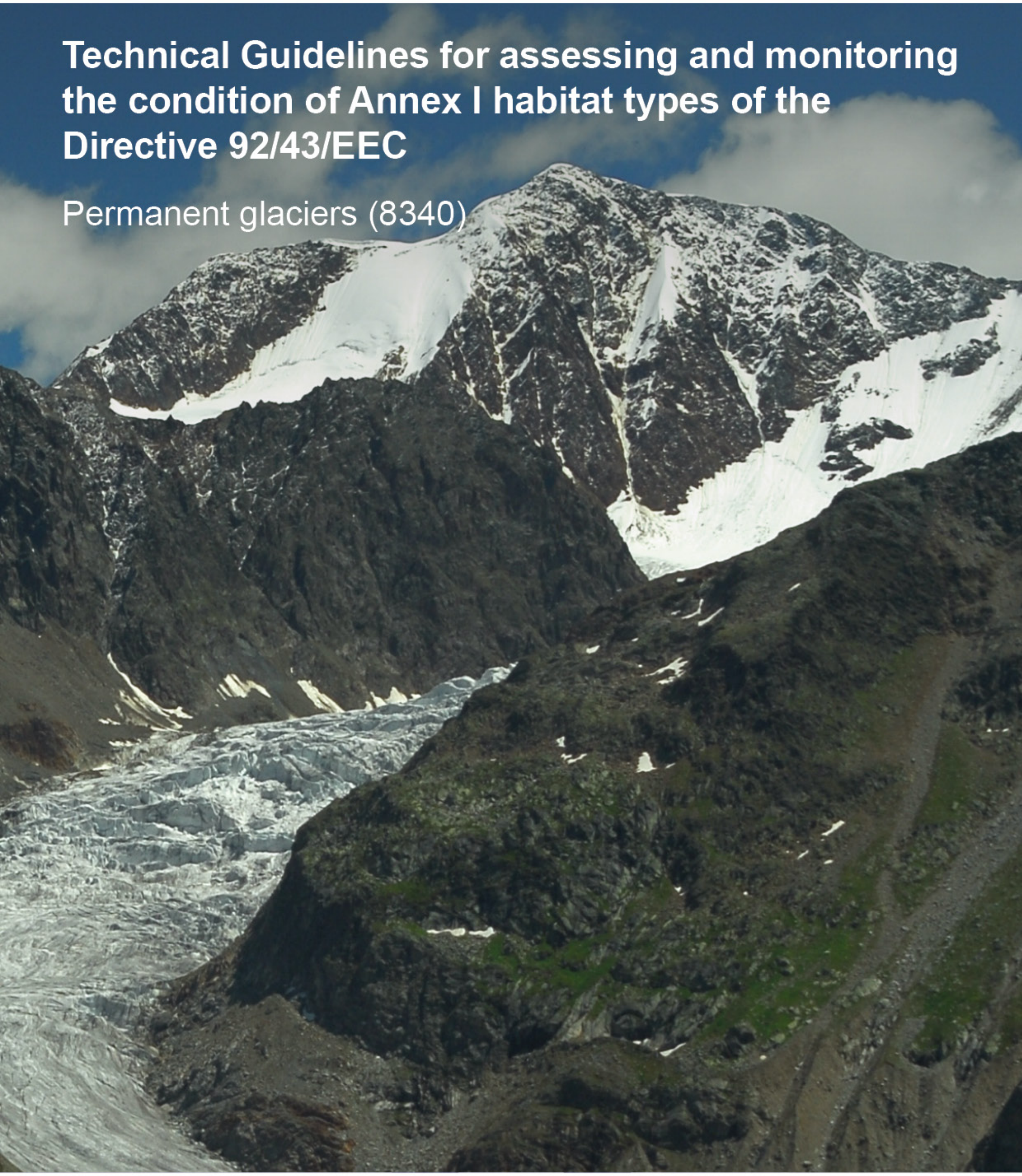
European Commission

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

Permanent glaciers (8340)



ATECMA

DAPHNE
Inštitút aplikovanej ekológie

Institute for European Environmental Policy

EUROPEAN COMMISSION

Directorate-General for Environment
Directorate D — Biodiversity
Unit D3 — Nature Conservation

E-mail: nature@ec.europa.eu

European Commission
B-1049 Brussels

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

Permanent glaciers (8340)

Jozef Šibík (Slovak Academy of Sciences)

Augusto Pérez-Alberti (ATECMA)

Ana Zuazu Bermejo (ATECMA)

This document must be cited as follows:

Šibík, J., Pérez-Alberti, A. & Zuazu Bermejo, A. (2025). Permanent glaciers (8340). 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 978-92-68-32022-8
https://doi.org/ 10.2779/6599558

Manuscript completed in September 2025

Luxembourg: Publications Office of the European Union, 2025

PDF ISBN 978-92-68-32022-8 doi:10.2779/6599558 KH-01-25-207-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 the ad-hoc group supporting the project, experts and representatives from EU Member States authorities and other relevant organisations 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 these 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

The interpretation manual includes in habitat type 8340 "Permanent glaciers" both rock glaciers and true glaciers (European Commission, 2013). In these Technical Guidelines, however, rock glaciers are covered by the document for habitat group 81 (scree), owing to their similarity to scree habitats, while true glaciers are addressed separately in this document.

The analysis of existing methodologies from EU Member States was based on the methodologies of Austria, Germany, Italy and Spain. These methodologies present a high level of similarity regarding the variables measured, which are mostly focused on physical characteristics (e.g., mass balance, ice thickness) with only one compositional variable (typical species) and one landscape variable (presence of disturbances) being measured. No threshold values are indicated and one aggregation system is presented. Different monitoring techniques are applied combining field work with remote sensing.

A set of essential and recommended variables for monitoring true glaciers are proposed for harmonisation of the methodologies used to assess the condition of these habitats. They are categorized into abiotic (e.g., mass balance, thickness), biotic (e.g. presence of microorganism), structural and functional (cover of plant functional diversity), and landscape (e.g., patch size, ice thickness).

Guidance on the definition of threshold values to determine good condition, for the aggregation of the measured variables at local and biogeographical scale, for monitoring protocols and sampling design are also included in this document.

The guidelines outline several priority areas for future efforts, such as the need to undertake a comprehensive ecological characterization of the habitat that includes all glacier-related environments, and the development of a large-scale and coordinated monitoring programme.

.

1. Definition and ecological characterisation

1.1 Definition and interpretation of habitats covered

Glaciers are accumulations of ice formed through glacial processes and are considered permanent on a human timescale. However, under conditions of global climate warming, melting and retreat—particularly in smaller glaciers—can lead to their complete disappearance within only a few decades. Composed primarily of recrystallised snow, glaciers display clear signs of movement, either downward or outward, driven by gravitational forces (Benn & Evans, 2014). They form through the processes of snow accumulation, compaction, and recrystallisation, while losing mass through evaporation, sublimation, or melting.

Two principal categories of glacial formations are recognised: traditional glaciers and rock glaciers. True glaciers are largely composed of massive ice bodies, whereas rock glaciers consist of a mixture of ice and rock debris. This distinction is important for understanding the diversity of glacial landscapes and their specific characteristics. Rock glaciers are accumulations of angular, poorly sorted rock blocks combined with ice, typically found in high-mountain environments. Their movement results from internal ice deformation (Giardino & Vitek, 1988; Barsch, 1996), usually taking the form of a lobe or tongue of debris.

The interpretation manual includes in habitat type 8340 "Permanent glaciers" both rock glaciers and true glaciers (European Commission, 2013). Due to their similar characteristics to scree habitats, rock glaciers are included within the monitoring guidelines developed for habitat group 81 (screes). Rock glaciers share notable similarities with scree environments, including their composition of rock debris and their capacity to support plant and arthropod communities. These formations serve as crucial refugia for cold-adapted species, owing to their distinctive microclimate and thermal inertia properties (Tampucci et al., 2017; Tampucci et al., 2015).

Habitat 8340 occurs throughout the alpine regions of Austria, Germany, Spain, France, Italy, Slovenia, and Sweden. The most recent assessment under Article 17 of the Habitats Directive for the period 2013-2018 revealed that all countries reported an unfavourable-bad conservation status for this habitat type (EIONET Portal[1]).

Snow and ice-dominated habitats encompass glaciers, snowfields, and cryoconite holes, all of which harbour diverse **microbial communities**. These communities are dominated by algae, bacteria, archaea, and fungi which play significant roles in global biogeochemical cycles (Anesio et al., 2017; Hoham & Remias, 2019; Lutz et al., 2017; Maccario et al., 2019;). These organisms are critical for primary production and biogeochemical processes. Snow and ice algae, particularly from the Chlamydomonadales and Zygnematales orders, are primary colonizers and net producers during the melt season, significantly influencing the ecosystem (Callaghan & Johansson, 2015; Lutz et al., 2017; Hoham & Remias, 2019).

These organisms have evolved specialized cryogenic adaptations including genetic resistance mechanisms and the production of secondary metabolites like carotenoids to protect against low temperatures and high UV radiation (Callaghan et al., 2005; Maccario et al., 2019). Critical adaptations include the formation of resistant cysts and production of ice-binding proteins and polyunsaturated fatty acids to reduce cellular damage from freeze-thaw cycles (Callaghan et

[1] https://nature-art17.eionet.europa.eu/article17/habitat/summary/?period=5&group=Rocky+habitats&subject=8340&region

al., 2005; Hoham & Remias, 2019), demonstrating remarkable biochemical innovations for survival in frozen environments.

The ecological and biogeochemical roles of snow and ice ecosystems contribute substantially to global elemental cycles. These systems support microbial activity that drives chemo-lithotrophic processes and nutrient transformations, playing vital roles in carbon and nutrient cycling (Maccario et al., 2019; Anesio et al., 2017; Ren et al., 2017). Microbial communities in these environments actively participate in complex biogeochemical transformations, with bacterial abundance and production rates being significantly higher in algae-containing environments compared to pristine conditions.

The presence of snow and ice algae also reduces surface albedo, accelerating the melting of snowpacks and glaciers, which has profound implications for climate change dynamics (Lutz et al., 2017; Hoham & Remias, 2019). This albedo reduction effect represents a critical feedback mechanism linking microbial activity to global climate patterns, demonstrating how microscopic organisms can influence planetary-scale processes and contribute to broader environmental systems through their biogeochemical functions.

Snowbed vegetation is characterised by specialised plant communities that are adapted to variations in snow depth and nutrient availability (Björk & Molau, 2007). Climate warming is modifying nutrient and trophic dynamics within these habitats, resulting in shifts in microbial community structure and function, with consequent impacts on downstream ecosystems (Callaghan & Johansson, 2015; Webster et al., 2018).

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

1.2.1 Ecological characterisation

Typology

Glaciers can be classified according to their geographical location, dimensions, and morphological characteristics. According to Benn and Evans (2014), mountain glaciers represent relatively small ice masses situated at elevated altitudes within mountainous terrain. The smallest category within this classification comprises cirque glaciers, which occupy distinctive hollows or bowl-shaped depressions carved into mountain slopes through glacial erosion processes.

As cirque glaciers advance downslope under gravitational forces, they frequently extend beyond their initial basins and spread into adjacent valleys, thereby transforming into valley glaciers. The morphological development and configuration of these valley glaciers is predominantly determined by the pre-existing topographical features of the landscape, including valley width, gradient, and bedrock geology.

When valley glaciers extend their terminus to sea level, they possess the capacity to carve deep, narrow coastal valleys through sustained erosional activity. These glacial systems are classified as fjord glaciers, and the distinctive valleys they create subsequently become fjords once seawater fills these depressions following ice retreat or melting. Alternatively, when a valley glacier flows beyond the confines of its valley and spreads across gentler slopes extending beyond a mountain range, it develops into a piedmont glacier, characterised by its fan-shaped or lobate terminus morphology.

In cases where glacial ice accumulates sufficiently to cover entire mountain ranges, these extensive ice masses form comprehensive ice caps that can completely obscure the underlying topography.

Glacier structure

A glacier is comprised of distinct zones defined by its mass balance. In the upper region, known as the accumulation zone, net ice accumulation is typically positive; here, snowfall and other forms of precipitation add more ice than is lost. This excess mass drives a flow of ice downslope, propelled by gravity, towards the glacier’s lower region—the ablation zone. In this zone, melting is intensified at the surface, resulting in considerable ice loss, especially at the glacier’s terminus. The snow line serves as the boundary between the accumulation and ablation zones.

The Pasterze glacier under the Grossglockner massif with Johannisberg peak in the background.Hohe Tauern mountains, Austria.
© Jozef Šibík, 2008.

The transfer of ice from the accumulation zone to the ablation zone is governed by two main influences: **mass balance** and **topographical characteristics**. The mass balance embodies the climatic aspect, representing how prevailing weather conditions regulate the glacier’s ice gain and loss. Meanwhile, factors such as slope angle, underlying bedrock structure, and the existence of water at the glacier’s base constitute the dynamic, physical component. These features shape how a glacier responds to climatic fluctuations, with periods of adjustment that may span several years to over a decade. Ultimately, the interplay between climatic conditions and physical structure determines the pace at which a glacier adapts to changes in its surrounding environment.

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

Abiotic characteristics

Geomorphology and dynamics

A glacier can change size by accumulation, which occurs through the addition of snowfall, compaction and recrystallization, and by ablation, the loss of mass resulting from melting, usually at lower altitudes where temperatures may exceed freezing in summer. The **mass balance of a glacier**, which is determined by the relationship between accumulation and ablation over a full season, dictates whether the glacier will grow or shrink. When accumulation exceeds ablation, the glacier gains mass and expands. Conversely, if ablation surpasses accumulation, the glacier loses mass and retreats. This dynamic equilibrium is crucial in determining the long-term behaviour and health of glaciers, reflecting their sensitivity to climatic conditions and environmental changes.

Glaciers move downslope under the force of gravity through two primary mechanisms: internal flow and basal sliding. Internal flow involves the deformation of ice crystals, which slide over each other like a deck of cards, resulting in the glacier's movement. The upper layers of glaciers are more brittle compared to the lower sections. As the lower part deforms through internal flow, the top can fracture, forming large cracks. These cracks are particularly noticeable when glaciers flow over sudden changes in topography. Basal sliding occurs when meltwater at the glacier's base reduces friction, effectively lubricating the surface and allowing the glacier to slide along its bed. This process is more common in temperate glaciers. This movement processes contribute to the dynamic nature of glaciers and their ability to shape landscapes over time. The interplay between internal flow and basal sliding, influenced by factors such as temperature and topography, determines the overall behaviour and movement patterns of different types of glaciers.

The **velocity** of glacial ice varies throughout the glacier's body, exhibiting a pattern influenced by its position within the glacier. Near the base and along the valley walls, the ice moves at its slowest pace due to friction with the surrounding surfaces. As distance from these areas increases, the ice velocity gradually rises. The fastest-moving ice is typically found in the centre and upper portions of the glacier, where it experiences less resistance. This velocity gradient creates a characteristic flow pattern, with the glacier's core moving more rapidly than its edges and base. Understanding these velocity variations is crucial for comprehending glacier dynamics and their overall movement (Greve & Blatter, 2009).

As a result of these movements, crevasses and fractures form from the friction against irregular terrain. Crevasses in glaciers result from variations in ice velocity within the glacier body. When two adjacent sections of rigid glacial ice move at different speeds or in different directions, they experience shear forces. These forces cause the ice to fracture, leading to the formation of crevasses (Greve & Blatter, 2009).

Climate characteristics

The evolution of glaciers is intimately linked to the climatic and meteorological conditions in their surrounding environment. Glaciers experience volumetric oscillations over time, which result from the balance between snow accumulation and the loss of ice and snow through melting or sublimation processes. This balance can be quantified by calculating the energy exchange on snowy or frozen surfaces, which depends on factors such as net radiation, sensible and latent heat fluxes, ground heat flux, and heat transmitted by rainfall. However, measuring these parameters requires complex instruments that are challenging to install and maintain in glacial environments.

Consequently, most studies focus on relating glacier fluctuations to changes in **precipitation and temperature**. These two parameters effectively summarize the complex physical phenomena governing a glacier's mass balance. Additionally, precipitation and temperature data are widely available from numerous locations with sufficient historical records to reliably analyse their variability and trends over time

Understanding the relationship between climatic oscillations and glacial dynamics requires a focus on the key variables that best summarize a glacier's mass balance: precipitation and melting. The amount of precipitation accumulated during the period when snowfall is predominant and freezing processes outweigh melting must be considered as well as the average temperature during the months when melting is the dominant process. These two factors provide essential insights into the accumulation and ablation phases of a glacier's annual cycle, respectively.

Glaciers are facing the threat of global warming. Glaciers around the world are rapidly retreating, thinning and losing mass (Hock & Huss, 2021). Although their total volume is small compared to the Greenland and Antarctic ice sheets, glaciers located outside the ice sheets have contributed significantly to recent sea level rise in terms of precipitation and melting around the world. On average, these glaciers experienced only slightly negative mass balances in the 1960s-80s, but mass loss has increased considerably since then. While rising air temperatures are the primary driver of glacier mass loss, the response of glaciers to this warming is complex and influenced by various factors. Changes in glacier geometry and interactions between ice and water at marine or lake-terminating glacial fronts can complicate this relationship. Although individual glacier advances do occur, they are uncommon and often result from dynamic processes that are not directly related to climate. Looking towards the future, projections indicate that glaciers worldwide may lose between 18% and 36% of their 2015 ice volume by the end of the 21st century, with the extent of loss depending on different emission scenarios.

Biotic characteristics

There is little literature on the biotic characteristics of permanent glaciers. However, it is now widely accepted that glaciers and ice sheets constitute unique habitats that host characteristic organisms and metabolically active populations that form communities and facilitate key connections with neighbouring ecosystems, all of which can be severely altered, reduced or lost following deglaciation (Stibal et al., 2020).

According to Gobbi et al., (2021) ice glaciers and rock glaciers host a wide variety of cold-adapted taxa, from bacteria to vertebrates. They have been included in the Natura 2000 network but their biodiversity remains poorly known. Although local extinctions and population decline of cold-adapted species due to shrinking glaciers and permafrost have already been documented, none of the species living in these habitats are listed in the annexes of the Habitats Directive.

The upper ice sheets of glaciers (**supraglacial ecosystem**) are the most biologically productive part of these frozen landscapes, hosting a diverse array of organisms and habitats (Jaroměřská et al., 2023). These ice sheets encompass several important ecological niches (Stibal et al., 2012). Dominating the upper ice sheet are glacial algae, true specialists of this environment. These photoautotrophs play a crucial role in ecosystem processes by accumulating photosynthetically derived autochthonous organic carbon, which in turn supports a range of heterotrophic glacial microorganisms (Williamson et al., 2019).

Cryoconite holes, depressions formed by the preferential melting of dark debris on the surface (Cook et al., 2016), constitute a biological hotspot on the surface of glaciers. These holes offer stable conditions opposed to the highly dynamic supraglacial environment. Within these miniature ecosystems, a complex web of life unfolds, featuring an array of microorganisms including bacteria, archaea, algae, and fungi, as well as rotifers, tardigrades, annelids, insects and crustaceans (Zawierucha et al., 2015). Cryoconite granules, formed inside the holes as a result of the interaction between mineral and glacial Cyanobacteria serve as storage units for organic matter and contribute to the reduction of albedo on glacier surfaces (Wejnerowski et al., 2023). On the Forni Glacier (Central Italian Alps), cryoconite granules have been observed over many years, with a mean ± SD size of 0.54 ± 0.20 mm (Rozwalak et al., 2022). The presence of radionuclides (proxy for longrange transport of anthropogenic originated contaminations) in glaciers and its relation to biotic component of cryoconite (organic matter, chlorophyll concentration, the ratio of cyanobacteria to all bacteria, and size of cryoconite granules) has also been examined in a study by Buda et al. (2023) focusing on ^{137}Cs, ^{210}Pb, ^{238}Pu, and $^{239+240}Pu$.

The ecological significance of glaciers extends beyond their resident microbiota. They serve as critical temporary habitats for a variety of alpine fauna, including invertebrates (Coleoptera Carabidae, Diptera, Chironomidae, Plecoptera, Araneae, Acarinae, Collembola), birds, and mammals (Gobbi et al., 2021). These larger animals often rely on the glacier's microscopic inhabitants or wind-deposited organic matter as food sources, forming intricate food webs in this seemingly inhospitable environment (Rosvold, 2016).

Englacial habitats encompass a diverse range of microenvironments within glacial ice, including gas bubbles, bulk ice, liquid water veins, englacial channels, and embedded debris. Rather than existing as isolated systems, these internal features maintain hydrological connections to the glacier surface through water percolation, enabling the transport of nutrients, dissolved organic matter, and microorganisms into deeper ice layers. Such connectivity indicates that englacial environments may contribute meaningfully to the cycling of organic carbon within the larger glacial ecosystem. Nonetheless, under the extreme and often nutrient-limited conditions typical of these settings, the englacial ecosystem primarily functions as a repository for inactive microorganisms and preserved genetic material (Makowska Zawierucha et al., 2022; Varliero et al., 2021).

The subglacial ecosystem of glaciers serves as a habitat for a wide spectrum of microorganisms, predominantly prokaryotes, displaying significant taxonomic and functional diversity. These microbes have evolved metabolic strategies that allow them to utilize various substrates under differing redox conditions, demonstrating remarkable adaptability within such unique environments (Tranter et al., 2005). Because sunlight is unable to penetrate the thick ice above, microbial communities are largely dependent on chemical energy sources, which are primarily derived from interactions with the underlying bedrock. This dependency highlights the complex interplay between biological communities and the geological substrates that sustain them.

Subglacial environments do not present a uniform landscape; rather, they encompass distinctive aquatic habitats, including subglacial lakes and marine brines. These settings represent some of the most isolated ecosystems found on Earth (Christner et al., 2014). Such aquatic systems host thousands of microbial taxa, each specialized for the physicochemical conditions of their locale. Given their extreme isolation and unique environmental constraints, it is highly likely that these habitats contain novel, previously undiscovered species, positioning them as potential hotspots for microbial discovery and biodiversity.

Climate change is exerting significant pressure on temperate glacial ecosystems. These ecosystems are particularly susceptible to the effects of global warming (Stibal et al., 2020). The rapid retreat and looming disappearance of these glaciers due to climate change present a pressing ecological challenge (Hotaling et al., 2017). This situation is especially concerning given our limited understanding of the biodiversity in these environments, which is known to include numerous endemic species.

A summary of key ecological characteristics of glaciers (true glaciers) and some examples of variables that are useful to measure them are presented in Table 1 below. The classification follows the Ecosystem Condition Typology proposed in the SEEA-EA Framework (United Nations, 2021). Key variables affecting glacier distribution include precipitation during the wettest month, altitude, annual mean temperature, and temperature seasonality.

Table 1. Ecological characterisation and selection of variables used to measure habitat condition of permanent glaciers

Ecological characteristics	Types	Description	Examples of associated variables
Abiotic characteristics	**Physical state characteristics**	Volume	- Mass balance
		Climate	- Snow precipitation (Precipitation generally or precipitation during the wettest months) - Annual mean temperature - Temperature seasonality (Wang et al., 2021) - Surface temperature - Basal temperature
		Length and depth	- Glacier length - Glacier depth - Annual retreat
	Chemical state characteristics	Geochemical characteristics of ice	- Organic matter - Organic carbon - Radionuclides
Biotic characteristics	**Compositional state characteristics**	Presence and abundance of species and groups	- Microorganisms - Algae - Fungus - Rotifers, tardigrades - Crustaceans, Annelids, Coleopters… - Vertebrates: birds and micromammals
	Structural state characteristics	Vegetation cover	- Cover of specific vegetation structures or individual species or functional types such as lichens, bryophytes, vascular plants.
	Functional state characteristics	Generalists vs specialists	- Glacier retreat impacts biodiversity, with generalist species benefiting from increased diversity as glaciers retreat, while specialist species adapted to glacial conditions may decline (Cauvy-Fraunié & Dangles 2019).
Landscape characteristics		Fragmentation	- As glaciers retreat, functional diversity in plant communities decreases, affecting carbon cycling and resource allocation, while taxonomic diversity may increase (Khelidj et al., 2024).
		Equilibrium-Line Altitude (ELA)	-The altitude where accumulation equals ablation. Changes in ELA can indicate shifts in climate conditions affecting the glacier (Dugdale, 1972)

Ecological characteristics	Types	Description	Examples of associated variables
Other		Presence of animal or human alterations Altered River Systems	-Not used until now, however proposed as valuable input. -The reduction in glacial meltwater affects river discharge, sediment load, and water temperature, leading to changes in the composition of aquatic communities. This includes increased richness and production of microorganisms, algae, and macroinvertebrates as glacial influence diminishes (Milner et al. 2009).

1.3 Selection of 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[2] (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.

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

- 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. 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[3], 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 has long been clear from the reports provided by the MSs, that the typical species concept was interpreted differently (Maciejewski, 2010), meaning that the lists produced have probably had limited value. Therefore, the consideration of "typical species" in the assessment of the habitat conservation status still needs to be discussed and clarified.

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.

Regarding the selection of typical species of permanent glaciers, three main categories can be considered. First, cold-adapted species encompass diverse taxa specialized for the extreme conditions of glaciers and permafrost (Gobbi et al., 2021). Second, specialist species are key indicators, as they are highly sensitive to glacier retreat (Cauvy-Fraunié & Dangles, 2019). Third, generalist species, often colonizing from downstream areas, may increase in abundance as glaciers shrink, providing an indirect signal of habitat change through shifts in community composition (Cauvy-Fraunié & Dangles, 2019).

Species sensitivity to retreat is shaped by geographic factors—such as glacier cover, isolation, and melting rates, and by biological traits like body size and trophic position, which influence resilience or vulnerability to environmental change (Cauvy-Fraunié & Dangles, 2019).

Biodiversity surveys at the Forni Glacier in the Central Italian Alps, one of the most thoroughly studied European glaciers, have documented a range of organisms—including mosses, fungi, arthropods, and tardigrades—inhabiting supraglacial surfaces and cryoconite holes. These studies also provide a reconstructed trophic web of the glacier ecosystem (Crosta et al., 2024).

Table 2 provides an illustrative list of species' groups that can be used as indicators to assess glaciers' habitat condition.

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

Table 2. Examples of habitat 8340 typical species

Taxonomic Group	Examples of species and genus	Reference
Microalgae (Chlorophyta, Zygnema-tophyceae)	*Chlamydomonas nivalis*	Remias et al., 2010
Invertebrate – Diptera, Chironomidae	*Diamesa* spp.	Montagna et al., 2016
Invertebrate – Coleoptera, Carabidae	*Nebria germari*	Valle et al., 2020
Saxifragaceae	*Saxifraga bryoides*	Cannone et al., 2008
Bryophyta		Valle et al., 2025
Bird – Hirundinidae	*Delichon urbicum*	Crosta et al., 2024
Bird – Passeridae	*Montifringilla nivalis*	Crosta et al., 2024
Mammal – Mustelidae	*Mustela erminea*	Crosta et al., 2024
Mammal – Leporidae	*Lepus timidus*	Crosta et al., 2024
Mammal – Bovidae	*Rupicapra rupicapra, Capra ibex*	Crosta et al., 2024

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

The present analysis is mainly based on the methodologies available from Austria (Ellmauer, 2005), Germany (Bayerische Akademie der Wissenschaften, 2021; BayLU, 2022), Italy (Angelini et al., 2019) and Spain (Perez-Alberti et al., 2019).

Apart from the methodology proposed by Ellmauer (2005), the condition assessment of glaciers in Austria relies on the annual reports produced by the Austrian alpine association (e.g., Lieb & Kellerer-Pirklbauer, 2021). The Austrian Alps were the focus of a comprehensive glacial study that encompassed 91 glaciers, carefully selected to represent a diverse range of sizes and locations across Austria's ice-covered mountain ranges. The sample included both diminutive ice formations and some of Austria's most expansive glaciers, with the largest ones covering areas of approximately 15 Km^2. The collected data are stored in the database of the World Glacier Monitoring Service (WGMS[4]) in Zurich, Switzerland.

For other countries with glaciers, no methodologies were found for the monitoring of this habitat in accordance with Article 17 of the Habitats Directive, although some information is available on this habitat type. The types of glaciers found France (black glaciers and rock glaciers) are described in the "Cahiers d'habitats" (Bensettiti et al., 2004) but no methods to monitor or to assess the condition of the habitat are provided. A document on permanent glaciers developed by the Swedish Environmental Protection Agency (Naturvårdsverket, 2011) indicates sufficient precipitation in the form of snow in relation to evaporation and melting as a variable important to the structure and function of the habitat but no values or thresholds are indicated.

Regarding monitoring of glaciers in Slovenia, no official methodologies have been found. However, according to research conducted by Triglav-Čekada and Gabrovec (2016) the monitoring of Triglav glacier in Slovenia employs a multi-faceted approach combining regular photography, geodetic measurements, and photogrammetry. Since 1976, monthly photographs have been taken using a Horizon panoramic non-metric camera from two fixed standpoints. Geodetic measurements of the glacier boundary and surface points began in 1952, with annual surveys conducted since 2007. Photogrammetric measurements, both aerial and ground-based, have been used to supplement these observations. The glacier's 3D boundary is analysed using an interactive method of absolute orientation with Horizon images, allowing for the calculation of 2D area and theoretical 3D volume.

Additionally, ground-penetrating radar surveys were conducted in 1999 and 2000 to measure glacier depth. This comprehensive monitoring approach is complemented by continuous weather data from the nearby Kredarica mountain hut, providing valuable insights into the glacier's response to climate variations and enabling detailed studies of very small glacier behaviour.

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

Most variables included in the methodologies analysed are related to physical characteristics of permanent glaciers, including mass balance, length and geometric variations, and to disturbances. Inventory of typical species is only presented in the methodologies of Italy and

[4] World Glacier Monitoring Service database: https://wgms.ch/

Germany. No threshold values are provided for any variable except for presence of typical glacial structure and disturbances measured in Germany and Austria

A summary overview of the variables measured by the MSs methodologies is presented in Table 3. Further details on the description of the variables are provided in Table 4.

Table 3. Overview of the variables used by the different methodologies consulted

Variable group	AT	DE	ES	IT
1. Abiotic characteristics				
1.1 Physical state characteristics				
Internal temperature				■
Surface velocity				■
Mass balance		■	■	■
Changes in area, length and depth. Geometric variations			■	
Ice thickness		■		
Glacier sensitivity to climate			■	
Completeness of glacier structure		■		
2. Biotic characteristics				
2.1 Compositional state characteristics				
Presence of characteristic species		■		■
3. Other				
Disturbance indicators	■	■		

The **mass balance** allows to measure annually, the mass variations of a glacier based on the difference between the mass accumulated with the snowfall in winter and spring and the mass lost due to the melting of snow and ice (ablation) in the summer season. Estimation of mass balance is indicated by three methodologies (Pérez-Alberti et al., 2019; Angelini et al., 2016 and Bayerische Akademie der Wissenschaften, 2021) and several methods are proposed to measure them. This indicator is obtained from repeated measurements, either directly (glaciological balance) or indirectly (hydrological balance) and is an important indicator as it reacts rapidly to climate (temperature and precipitation), as opposed to changes in longitude (reaction in a few years to centuries depending on the length/slope of the glacier).

The methodology from Bavaria (Bayerische Akademie der Wissenschaften, 2021) measures mass balance in autumn, when the seasonal snow has melted and the remaining firn is at its minimum and is expressed as a water equivalent over the glacier’s entire surface. A positive mass balance indicates more snow gained than ice lost, while a negative balance shows net melting.

Monitoring the mass balance of a glacier is carried out globally according to different methodologies: the most widespread and robust is represented by the glaciological or ablatometric method (Bamber & Payne, 2004). To quantify the balance, it is necessary to estimate the winter accumulation and the summer melting. The estimate of the accumulation value is carried out at the end of spring (end of May) by measuring the height of the snowpack and the density of the snow in some points of the glacier. The summer melting is measured at the end of September using wooden or aluminium rods stuck in the ice (ablatometric stakes) which are used as a reference for the progressive lowering of the surface.

The value of the glacier behaviour, detected in correspondence with some significant points and considered homogeneous of portions of the glacier, is extrapolated to the entire surface and returned in the form of net specific balance, expressed in mm of equivalent water (Angelini et al. 2016).

In the methodology available from Spain (Pérez-Alberti et al., 2019) photogrammetric restitution, laser scanning, vertical analysis of the balance sheet and glacial equilibrium line altitude are also proposed.

Changes in occupied area and length is also indicated ad it is proposed to be measured by GIS mapping from orthophotographs. **Speed of movement of surface** is indicated by Angelini et al., (2016) but it has not been further described. Changes in glacier thickness is indicated to be measured with GeoRadar mapping and dynamics and movements of the glacier structures is proposed but no measurement method is indicated.

The assessment of **glacier depth or thickness** is an estimation of the volume of water stored in the ice, a parameter that is becoming increasingly important in the strategies for using the resource in a context of progressive reduction in water availability (Angelini et al., 2016). Ice thickness and total volume are determined according to the Bavarian Glacier report using geophysical techniques such as ground-penetrating radar (Bayerische Akademie der Wissenschaften, 2021). These measurements reveal how much ice remains and how quickly it is being lost.

The study of these indicators provides valuable information on the response of a glacier to accumulated mass changes. Correlation between **glacier dynamics and changes in climate** is presented in the methodology of Spain (Pérez-Albert et al., 2019). Only one methodology (Angelini et al., 2016) measures internal temperature but no methods are indicated.

The measurement of the **retreat of the glacier front**, data historically acquired by glaciological surveys through direct measurements from a stronghold, and now also carried out with the aid of new technologies such as GNSS surveys or on the basis of satellite, aerial or UAV images, allows us to quantify another parameter directly related to climate change and to maintain an uninterrupted series of observations spanning decades, sometimes centuries.

Presence of **typical structural elements** of glaciers is described by the methodology of Germany (BayLU, 2022) and the abundance of these elements is considered an indication of good condition. Presence of anthropogenic disturbances is also measured by Austria (Ellmauer, 2005) and Bavaria (BayLU, 2022).

For rock glaciers, the most significant indicators are represented by the internal structure (derived from geophysical investigations such as electrical tomography and reflection seismic), the internal temperature and the speed of movement of the surface (Angelini et al., 2016).

Regarding **biotic variables**, typical species including plants, algae and invertebrates are proposed in Germany (BayLU, 2022) but no threshold values are indicated. In the Italian methodology, according to Angelini et al. (2016), glaciers are generally devoid of phanerogam species. Only in the case of black glaciers and rock glaciers above the detritus is it possible to recognise the presence of herbaceous, shrub and tree species. The methodology add that the conservation status of glaciers can be effectively assessed through monitoring techniques that do not concern the presence of typical species.

The methodology from the Bayerische Akademie der Wissenschaften (2021) highlights the relevance of documenting debris cover due to its influence on melt rates: thin layers of rock and sediment can increase melting by absorbing more sunlight, while thick layers act as insulation and slow the melt. However, it is not clear whether this variable is measured or not.

Table 4. Variables used by the methodologies analysed

Variables names	Metrics	Measurement methods	Examples of thresholds	MS and references
1. Abiotic characteristics				
1.1 Physical state characteristics				
Internal temperature	ºC	Not provided	Not provided	**IT**: Angelini et al., (2016)
Surface velocity	Not provided	Not provided	Not provided	**IT**: Angelini et al., (2016)
Mass balance	Not provided	**ES**: Measurement by topographic survey of the terrain. Several methodologies, as photogrammetric restitution, laser scanning, vertical analysis of the balance sheet, glacial equilibrium line altitude (ELA). **IT**: the mass balance survey can be carried out with different methodologies, following standards defined at an international level (Bamber & Payne, 2004). The glaciological (or ablatometric) method, the most widespread, involves the estimate of accumulation in the month of May and the measurement of summer ablation by the end of September. An intermediate measurement, theoretically not necessary, is now an established practice among the glaciological surveyors of the Italian bodies that deal with monitoring. **DE**: mass balance measured in autumn and over a year	Not provided	**ES**: Perez-Alberti et al., (2019) **IT**: Angelini et al., (2016) **DE**: Bayerische Akademie der Wissenschaften (2021)
Changes in area and length	m	GIS mapping from orthophotographs of the National Aerial Orthophotography Plan (PNOA) following the methodology explained above. Every 5 years	Not provided	**ES**: Perez-Alberti et al., (2019)
Changes in depth	m	GeoRadar mapping. Periodicity according to possibilities.	Not provided	**ES**: Perez-Alberti et al., (2019)
Geometric variations	mm	The dynamics of a glacier can be analysed by studying the displacement of beacons installed on the glacier that serve to estimate the balance and its change in height from a fixed point.	Not provided	**ES**: Perez-Alberti et al., (2019)

Variables names	Metrics	Measurement methods	Examples of thresholds	MS and references
Ice thickness and total volume	m	Geophysical techniques: ground-penetrating radar	Not provided	**DE**: Bayerische Akademie der Wissenschaften, (2021)
Glacier sensitivity to climate	Not provided	It consists of identifying the correlations between the evolution of a glacier and the climate. These analyses are based on the direct study of the processes occurring on the surface of the glacier based on an energy balance.	Not provided	**ES**: Perez-Alberti et al., (2019)
Completeness of glacier structure	Presence of typical features	Visual expert inspection to detect presence of glacier crevasses, coverage of glacier with sand, gravel or rocks, streams of meltwater or young side moraines. Presence of ice as well as old snow.	A = at least two of typical features present; B = one of typical features present; C = does not reach B	**DE**: BayLu (2022)
1.2 Chemical state characteristics				
Typical species inventory	Presence	**DE**: Species inventory according to list of typical species (plants, algae and fauna). Vegetation in area immediately in front of tongue of glacier.	**DE**: A=Presence of Chlamydomonas nivalis, or six species from a list; B = presence of 4 species from list; C = does not fulfill B	**DE**: BayLu (2022) IT: Angelini et al., (2016)
3. Landscape characteristics				
Disturbance indicators on glacier	Not provided	Visual inspection to detect presence of impacts of recreational use (e.g. skiing), extent of glacier melting due to climate change.	**DE**: A = no evidence of recreational use and no or negligible reduction of glacier ice mass; B = moderate signs of recreational use and reduction of glacier ice mass; C = strong pressure from recreational use (e.g. presence of ski lift) and/or strong reduction of glacier ice mass. **AT**: A = no visible impairments (e.g., recreational use etc.); B = Medium: minor impairments (e.g. hiking routes) visible; C = significant impairments (e.g. development with ascent aids etc.)	**DE**: BayLu (2022) **AT**: Ellmauer (2005)

2.2 Definition of ranges and thresholds to obtain condition indicators

Only qualitative categories are indicated as reference values. The methodologies from Germany (BayLu, 2022) and Austria (Ellmauer, 2005) apply qualitative categories that indicate excellent (A), good (B) and medium-poor (C) condition. These categories are established and assessed by experts' judgment.

For instance, as regards the variable of presence of typical glacier structures (BayLU, 2022), detection of presence of glaciers crevasses, streams of meltwater and other elements is categorized as: (A) highly present, (B) largely present and (C) partially present.

2.3 Aggregation methods at local scale

Regarding the Spanish (Pérez-Albert et al., 2019) and Italian (Angelini et al., 2016) methodologies, no aggregation methods for the variables measured at the local scale are described.

For Austria (Ellmauer, 2005) and Germany (BayLU, 2022) an aggregation method has been developed, which is common for all habitat types and not specific for permanent glaciers. It follows categorical majority rules which establishes the habitat condition in the monitoring station according to pre-established combinations of ordinal condition categories (A, B, C). In these methodologies, three variable groups are established: 1) completeness of the typical habitat structures, 2) completeness of the habitat typical species inventory, 3) impairments (Kroiher et al., 2017). The assessment provides partial results for each set. These results are then aggregated following a majority rule see example below).

Box 1. Example of categorical majority rules (combination of qualitative assessment of variables) in Germany

Variables are included in the following three groups:

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

A categorical status is given to each of these variable groups: Excellent (A), Good (B) and Medium-poor (C).

Subsequently, the following rules are applied to the results of the assessment of the three groups of variables:

- All three criteria share the same status -> common status condition
- Two criteria share the same status -> in general, more common status condition, e.g. 2 Excellent and 1 Good -> Excellent
- 1 Excellent, 1 Good and 1 Medium-poor -> Good status condition
- Excellent and 1 Medium-Poor -> Good status
- If there is a C rating, an overall rating of A is no possible.

2.4 Aggregation methods at biogeographical scale

The aggregation of local assessment to obtain an evaluation of the habitat condition at the biogeographical should have followed the recommendations from the Art. 17 reporting guidelines for the period 2013-2018, which establish that the status of the 'structure and functions' parameter is 'favourable' if 90% of the habitat area is considered in 'good' condition, it is 'unfavourable-bad' if more than 25% of the habitat area is reported as 'not in good condition' and is 'unfavourable-inadequate' in intermediate percentages.

This rule however requires that the monitoring is carried out in a sufficiently representative area, including relevant locations and a statistically significant number of samples. The methods applied to ensure this requirement are however not fully described or documented in the methodologies considered in this analysis.

2.5 Selection of localities

Not all the methodologies present a clear explanation of the criteria followed to select the localities for assessment and monitoring the habitat condition.

Pérez-Alberti et al., (2019) indicates the use of cartography for the detection of 11 spots where glaciers are potentially located at an average altitude above 2.700 m, which favours low temperatures and precipitation in the form of snow. However, their actual presence was not verified. Glaciers in Spain are located in the Central Pyrenees in four main areas (Infiernos, Monte Perdido, Posets and Maladeta).

Angelini et al (2016) indicates the use of 1:10,000 cartographic scale to locate the areas with glaciers in Italy.

Although the main glaciers in Austria are well known, the methodology available for habitats monitoring (Ellmauer, 2005) does not provide information regarding the localities for monitoring beyond the occurrence of glaciers in the Alpine region above 2.700m and the indication that the habitat type should be recorded from an area of at least 10 ha of permanent ice surface. It also indicates that the immediate glacier forefield with the most recent ground and terminal moraines should be included in the delimitation of the area occupied by habitat 8340. However, a glacier monitoring programme coordinated by the University of Innsbruck is measuring glacier mass balance of 13 Austrain glaciers[5] (Goldbergkees, Hallstaetter Gletscher, Hintereisferner, Jamtalferner Kesselwandferner, Kleinfleisskees, Mullwitzkees, Pasterzenkees, Stubacher Sonnblickkees, Vernagtferner and Wurtenkees). It also uses glaciological data in the reconstruction of former climate states.

Regarding the monitoring of glaciers in Bavaria, it is not clear whether a total census is applied or which criteria are followed to select the localities. There are currently still four glaciers in the Bavarian Alps. These are the Northern Schneeferner on the Zugspitzplatt and the neighbouring Höllentalferner as well as the Blaueis and Watzmann glaciers in Berchtesgadener Land. The last remnant of ice on the Southern Schneeferner lost its status as a glacier in September 2022[6].

[5] https://www.wdc-climate.de/ui/project?acronym=GLACIER_MONITORING_AUSTRIA

[6] Glaciers of the Bavarian Alps http://www.bayerische-gletscher.de/index.htm

2.6 General monitoring and sampling methods

The methodologies do not provide enough information on the monitoring and sampling protocols (number of samples, size of sampling plots…).

The methodologies from Italy (Angelini et al., 2016) indicates a sampling period for the estimation of the accumulation value at the end of spring (end of May) by measuring the snowpack height and snow density at certain points on the glacier. The summer melt is measured at the end of September using wooden or aluminium poles driven into the ice (ablatometer poles) which are used as a reference for the progressive lowering of the surface.

Angelini et al. (2016) also indicates that data on cryosphere at planetary level is collected, analysed by the World Glacier Monitoring Service (WGMS) and published online in the Global Glacier Change Bulletin[7] and that specific information can be retrieved from that database.

As it has been previously indicated, annual reports on the condition of Austrian glaciers are produced by the Austrian alpine association (e.g., Lieb & Kellerer-Pirklbauer, 2021) and available at the WGMS.

Field measurements conducted by the (Bayerische Akademie der Wissenschaften, 2021) are complemented by satellite-based methods that can assess changes in glacier area, volume, and even velocity over large regions, albeit with lower spatial resolution than ground surveys. The integration of long-term datasets from both field and remote observations allows to detect meaningful trends emerge only from sustained monitoring over many years.

2.7 Other relevant methodologies

At the international scale, a variety of methodologies and projects are dedicated to glacier monitoring.

The **Glacial Monitoring of Switzerland (GLAMOS)**[8] is a comprehensive program aimed at studying long-term glacier changes in the Swiss Alps. It is a collaborative effort involving ETH Zurich, the University of Fribourg, and the University of Zurich, coordinated by the Swiss Academy of Sciences. GLAMOS collects data on glacier length changes for over 100 glaciers annually, measures mass balance and surface movement on selected glaciers and determines ice volume changes for numerous glaciers every 5-10 years. The program also compiles glacier inventories and monitors firn and ice temperatures. Funded by various Swiss federal agencies, GLAMOS provides crucial information on glacier response to climate change, disseminates results to international data centres, and makes the data available to researchers and the public through reports and an online data portal.

GLAMOS has developed a comprehensive manual titled “A Best Practice Guide for Long-term Glacier Monitoring in Switzerland” (Kurzböck & Huss, 2021). This guide encapsulates the current state of glacier monitoring practices in Switzerland as of 2020 and provides detailed information on the methodologies employed by GLAMOS. The guide states that GLAMOS is currently gathering data for length change, mass balance, volume change, surface flow speed, glacier inventories, and englacial temperature (Kurzböck & Huss, 2021).

The document offers insights into the rationale, advantages, and limitations of various monitoring techniques. While the authors intend for this guide to serve as a valuable resource for other monitoring initiatives, they emphasize that the methods described are specifically tailored

[7] Global Glacier Change Bulletin of the World Glacier Monitoring Service: www.wgms.ch
[8] Glacial Monitoring of Switzerland https://www.glamos.ch/en/#/B43-03

to Swiss glacial environments and may require adaptation for use in different geographical contexts.

Regarding variables for the monitoring of glaciers, Karpilo (2009) of the U.S. National Park Service outlines a set of control factors that influence glacier health, many of which also play a role in glacier formation. While these factors do not directly indicate the current condition of permanent glaciers, monitoring them can provide valuable context and a clearer understanding of the environments in which glaciers exist. Key factors include high, water-rich precipitation that boosts accumulation; low annual and summer temperatures, low insolation, low wind, and high humidity, which reduce ablation and help retain snow; high elevations that receive more precipitation and maintain lower temperatures; and low surface gradients that slow ice movement from accumulation to ablation zones. High latitudes lower both insolation and temperatures, while maritime locations bring moist air masses that increase snowfall. Poleward and leeward slopes reduce melt and capture drifting snow. Large accumulation areas, frequent avalanches, and the absence of water or cliff termini limit ice loss. Frequent landslides and thick debris cover insulate the ice, and low geothermal heat reduces basal melting.

Karpilo (2009) also proposes a set of vital signs and monitoring methods, which align with the variables described in Section 2.1: glacier mass balance, glacier terminus position, glacier area, and glacier velocity.

2.8 Conclusions

The methodologies consulted in this chapter cover most of the European regions where glaciers can be found, being from Austria, Germany, Spain and Italy with the exception of France, Slovenia and Sweeden. The methodologies present a lot of similarities in the variables and methodologies applied as well as the variables that are not considered in the monitoring.

Glaciers are characterised by accumulations of ice in environments where vegetation and fauna may occur, but are far less abundant than in other habitats owing to the harsh and specific climatic conditions. Accordingly, it is consistent with the nature of this habitat that the methodologies reviewed focus primarily on measuring abiotic physical characteristics rather than biotic ones, with the exception of two methodologies recording presence of typical species (Angelini et al., 2016; BayLU, 2022). The physical variables presented in the methodologies focus on changes in volume, length and mass of the glacier with mass balance being the variable most commonly addressed across the methodologies and the European and international glacier monitoring initiatives. Mass balance is the variable that best informs on the evolution and condition of the glacier since it is the result of the gain and loses during time where a maintained reduction on mass balance and informing on the degradation of the habitat. The importance of this characteristic of the glacier is also supported by the international databases collecting data primally of this variable. The other physical characteristics measures are changes in length and area, changes in depth and thickness.

Sensitivity to climate is only specified as a variable in the methodologies of Pérez-Albert et. al., (2019). Nonetheless, the other consulted methodologies discuss sensitivity of glaciers to climate and to climate change.

Concerning the absence of chemical characteristics measured, it can be understood that chemical variables have not being included due to the increase in budgetary and resource efforts that involves laboratory analysis. However, organic matter has a major role in the biotic life of cryoconite and nutrient cycle. Therefore, measuring its availability is needed to characterise the biotic component and food web of the habitat and should be included in a monitoring programme aiming to obtain information on the glacial habitat as a whole, considering the microbial communities and other biotic elements. Other chemical components that can be relevant in glaciers are radionucleotides. Thus, measuring their presence and relation to the biotic glacier community should be included as part of a monitoring programme that wants to assess the ecological characteristics of glacier habitats.

Another notable absence is the measurement of biotic characteristics. Apart from two methodologies that record the presence of typical species, no variables are included to assess the biotic structure or function of the habitat. In environments such as glaciers, which are largely defined by their physical characteristics, monitoring typically focuses on these features. However, glacier habitats also include biotic communities of microbes, flora, and fauna, which should not be overlooked in a habitat condition assessment.

Overall, no methodologies but two provide threshold values for the variables. Ellmauer (2005) and BayLU (2022) indicate qualitative categories to indicate different conservation status and these are based on expert opinion.

The methodologies do not provide information on the sampling protocols on regards to use the number or size of samples. The methodologies combine field work with remote sensing technologies. Different techniques presented for the measurement of mass balance and most physical variables are measured using laser, GPR, aerial photography, … all of which are standard methods commonly used in glacier monitoring. Although only Angelini et al. (2016) explicitly refers to the possible use of data from WGMS, and Austria has a dedicated monitoring programme for its glaciers, the other methodologies nonetheless acknowledge the availability of glacier databases and climatic models, even if these are not specified as part of their monitoring programmes.

No aggregation system of variables is provided except for Ellamuer (2005) and BayLU (2022).

Due to its extreme importance on climate regulation and water supply, a lot of effort is put on glacier monitoring at a global level. The World Glacier Monitoring Service, World Data Climate Centre and Glacial Monitoring of Switzerland are examples of the coordinated and extensive monitoring of glacier mass balance and fluctuations. As a habitat of community interest, the methodologies developed by the Member States are more limited. However, as it has been indicated, some of these Member States (e.g. Austria and Italy) already rely on these global institutions to obtain data of their own glaciers.

In conclusion, glacier monitoring across the consulted methodologies relies predominantly on physical variables (primarily mass balance, glacier length, and thickness), while biotic characteristics are generally underrepresented. The monitoring methods used for collecting data are standard and widely used in glacier monitoring tradition and there are several public databases at a European and at an international level that allow for a reduction in the monitoring effort having the possibility of retrieving data easily from them.

Further efforts to harmonise glacier monitoring should focus on increasing the representation of variables that reflect the biotic characteristics of this habitat.

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, as well as in other glacier monitoring programmes described in Section 2.7, 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.

Due to the nature of this habitat, these variables are mainly focused on measuring physical characteristics of the glaciers, although associated species should also be taken into account. Measurement methods are further described below.

The proposed conditional variables are classified into essential and recommended variables. 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., surface temperature). Essential variables correspond to characteristics that are essential for the habitat and describe its condition (e.g., mass balance). Recommended variables correspond to common variables which are relevant but that can be neglected to be measured in some contexts (e.g., organic carbon).

Climatic variables are proposed as descriptive variables that allow to retrieve information on the context of the glacier.

Snow precipitation and both surface and basal temperature influence the glacier's mass balance. Data for these variables can be obtained from meteorological data stations and remote sensing. Basal temperature can be measured by placing thermistors or other thermal sensors in drilled boreholes at different depths within the ice column (Price et al., 2002). Remote sensing like Landsat (Gök et al., 2024) or ground-based thermal infrared imagery which allows to obtain spatially distributed surface temperature data (Aubry-Wake et al., 2015).

Regarding essential variables, **mass balance** represents the water equivalent of glacier gains and losses over a specific period as a result from accumulation and ablation (Cogley, 2010). This metric responds rapidly to climatic variables such as temperature and precipitation. Mass balance can be measured through different standard techniques such as glaciological mass balance assessment with stake readings or photogrammetry (Geissler et al., 2021).

The **thickness of glacier ice** is a key factor in forecasting glaciers' retreat (Welty et al., 2020). Glacier thickness can be determined through geophysical measurements, using ground-based or helicopter-borne applications of GPR (Machguth et al., 2006). These methods are based on the transmission, reflection, and subsequent detection of radio waves.

Surface velocity measurements, obtained through repeated GPS surveys or feature tracking in aerial and satellite imagery, provide critical insights into ice flow dynamics and their response to mass balance variations (Ahn et al., 2021). Glacier length provides data on glacier changes and can be measured using different techniques such as GPS surveys, aerial imagery or digital elevation models (DEM) (Ji et al., 2017).

Regarding **chemical variables**, organic matter monitoring in glacier environments provides insights into ecosystem functioning and carbon cycling. **Organic carbon** assessment involves quantifying both dissolved and particulate organic carbon in glacial waters, ice cores, and sediment samples to understand carbon storage, transport, and transformation processes within the glacier system. Concentration of **organic matter** can be obtained through high temperature combustion (Chifflard et al., 2024) or and its characterization using fluorescence spectroscopy (Dubnick et al., 2010). More recent organic matter analysis use nano-UPLC-nano-ESI-HRMS to detect major molecular species in ice core (Zangrando et al., 2020). Total organic carbon can be assessed through catalytic combustion and non-dispersive infrared detection (Lutz et al., 2015; Koziol et al., 2018). Radionuclides can be detected using gamma spectrometry (Buda et al., 2024).

Biotic essential variables focus on the presence of cryosphere **microbial community** and microfauna, invertebrates and vertebrates.

The cryosphere, comprising glaciers and permafrost, delivers essential ecosystem services and shapes human interactions with high-mountain environments. Although often perceived as inhospitable, research on glacial biodiversity has been increasing, particularly within European mountain ranges. Glaciers and associated landforms provide habitats for a wide range of cold-adapted species, from bacteria to vertebrates. Nevertheless, much of this biodiversity remains insufficiently documented (Gobbi et al., 2021). In particular, the fauna inhabiting cryoconite holes on Alpine glaciers is still poorly known and largely understudied.

Monitoring the presence and activity of microorganisms in glacial environments is crucial for understanding their ecological and biogeochemical impacts. On the surface of glaciers, **heterotrophic algae** and microorganisms play a significant role in nutrient cycling and ice melting. These organisms rely on organic carbon sources, such as algal exudates, to sustain their metabolic processes, which can amplify surface ice melting rates and influence downstream ecosystems through nutrient export in meltwater. At the base of glaciers, microbial communities capable of metabolizing a wide variety of substrates under different redox conditions are essential for energy production in oxygen-limited environments. These microorganisms utilize alternative electron donors and acceptors, such as iron, sulphate, or nitrate, enabling survival through diverse metabolic pathways like fermentation or anaerobic respiration. Together, these microbial processes at the surface and base of glaciers highlight their adaptability and critical role in shaping glacial ecosystems amidst changing environmental conditions.

Microorganisms including bacteria and archaea are sampled from ice, meltwater, and cryoconite holes using sterile collection techniques. Algae monitoring focuses on both supraglacial communities and those within cryoconite ecosystems, while fungi are assessed for their roles in organic matter decomposition and nutrient cycling. **Microscopic fauna** including rotifers and tardigrades, as well as crustaceans, annelids and coleoptera, require microscopic identification and enumeration. However, Environmental DNA (eDNA) metabarcoding has emerged as a powerful, non-invasive tool for monitoring biodiversity in glacier ecosystems, offering significant advantages over traditional morphological identification methods (Varotto et al., 2021). This approach is particularly valuable for detecting microbial communities and invertebrates in challenging high-altitude environments where conventional sampling may be difficult or insufficient. This approach is particularly valuable for detecting microbial communities and invertebrates in challenging high-altitude environments where conventional sampling may be difficult or insufficient. Presence of vascular plants and cryptograms, as well as presence of vertebrates is recorded by visual assessment based on local or regional species reference lists.

The proportion of land area occupied by individual groups or functional types (lichens, bryophytes, vascular plants), measured as a percent-age of coverage is proposed as an essential structural and functional variable. Lichens and bryophytes contribute to soil stabilisation and nutrient cycling, whereas vascular plants typically form the main structural framework of vegetation, influencing energy flow, habitat diversity, and overall ecosystem dynamics. Assessing the cover of these groups provides valuable insight into patterns of biodiversity and productivity in this habitat, where their presence is rare.

Regarding **landscape variables**, glacier's extent (i.e., total area of the glacier) and terminus position are proposed. Both variables provide information on glacier's changes over time and can be measured through remote sensing techniques using Landsat-type medium-resolution optical satellite sensors (Nijhawan & Jain, 2018; Robbins et al., 2024). The presence of fragmenting infrastructures in the area is proposed to be recorded during fieldwork or assessed using aerial image or remote sensing techniques. Detecting the presence of these infrastructures can be easily measured and provide information on structural fragmentation of the habitat.

Table 5. Proposals for condition variables for assessing and monitoring habitat type 8340 (permanent glaciers)

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

Variables	App	Metrics	Measurement methods
1. Abiotic characteristics			
1.1 Physical state characteristics			
Snow precipitation	Descriptive	mm	Measured with nivometer or retrieved from meteorological stations.
Surface temperature	Descriptive	ºC	Temperature measurement sensors. Remote sensing.
Basal temperature	Descriptive	ºC	Temperature measurement sensors.
Mass balance	Essential	meters of water equivalent (m.w.e.) or millimeters of water equivalent (mm.w.e.)	Several methodologies can be used (e.g., photogrammetric method, glaciological method).
Glacier thickness	Essential	m	Thickness can be measured using ground-penetrating radar (GPR).
Surface velocity	Essential	Metres per year (m/yr) or metres per day (m/d)	GPS surveys or feature tracking in aerial/satellite images.
Glacial length	Essential	m or km	Several methodologies can be used (e.g., topographic maps, GPS survey, aerial imagery, digital elevation models (DEM)).
1.2 Chemical state characteristics			
Organic matter	Essential	µg L^{-1}	Chemical analyses on water from dated strata.
Organic carbon	Recommended	Mg a^{-1}	Chemical analyses on water from dated strata.
Radionuclides	Recommended	Bq kg^{-1}	Chemical analyses on water from dated strata.

Variables	App	Metrics	Measurement methods
2. Abiotic characteristics			
2.1 Compositional state characteristics			
Presence of vascular plants and cryptograms	Essential	Presence	Visual inspection according to list of characteristic species.
Presence of Microorganism: Algae, Fungi, Rotifers, tardigrades,	Essential	Presence	Field samples and laboratory analysis (eDNA).
Presence of Crustaceans, Annelids, Coleoptera	Recommended	Presence	Field samples and laboratory analysis (eDNA).
Presence of Vertebrates: birds and micromammals	Essential	Presence	Visual inspection according to list of characteristic species.
2.2 Structural / Functional state characteristics			
Cover of individual groups or functional types	Essential	% of area covered by each group	Visual estimation by grids or plots. Point or 'point-intercept' method. Photogrammetry or digital analysis.
3. Landscape characteristics			
Glacier extent	Essential	km^2 (area)	Aerial photographs, or satellite images.
Terminus position	Essential	m or km	Aerial photographs, or satellite images.
Presence of fragmenting structures	Essential	Presence and coverage of the infrastructure.	Visual assessment: GIS, aerial images.

App.: Application

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

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

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

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

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

These guidelines do not aim to prescribe specific threshold values. Rather, they outline the main 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 normalized harmonization 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. Measurement values are normalised using reference levels and reference conditions, allowing comparison across variables. 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).

3.3 Guidelines for the aggregation of variables at the local level

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

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

3.3.1 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 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

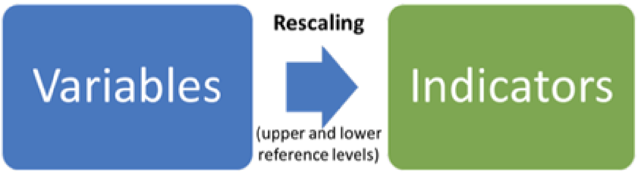
Differential weighting of indicators may be applied when calculating sums, means, or medians. The choice of weighting system should reflect the relative importance of each indicator in determining the overall condition of the ecosystem. Ideally, the approach should be supported by a clear scientific 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 1. 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:

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

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

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

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

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

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

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

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

3.4 Guidelines for aggregation at the biogeographical region scale

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 Guidelines on general sampling methods and protocols

In establishing guidelines for the evaluation of the subsequent sampling methods and protocols, particular attention should be given to their alignment with the criteria employed in determining the minimum number of monitoring localities:

1. Variable measurement scales: Certain variables, such as glacier length, extent, and mass balance, can be measured at the scale of the entire glacier. In contrast, chemical and biotic parameters should be assessed at more localized scales, such as monitoring plots or stations.

2. Monitoring plot placement: Monitoring plots should be strategically placed in different areas of the glacier to capture variations in environmental conditions. Considerations for placement should include:

- **Location:** Select sites near meltwater streams, on different slopes, or in areas with varying exposure to sunlight.
- **Size:** Plots should be large enough to capture the ecological features of interest but manageable for data collection (e.g., 10m x 10m) even from remote sensing (minimum size of one pixel, e.g. from Sentinel 2 data).
- **Number of plots:** The total number of plots should be determined based on the glacier's size and ecological diversity, ensuring a sufficient sample size for statistical analysis.

3. Monitoring frequency and timing: Establish a clear monitoring schedule that outlines how often data will be collected (e.g., bi-annually, annually) and the timing within the year (e.g., late spring for snowmelt, late summer for vegetation assessments). This schedule should consider seasonal changes and climatic conditions that may affect glacier dynamics.

3.6 Selecting monitoring localities and sampling design

The selection of sampling localities - along with the sample size (number of plots) and power -is essential to ensure that the results of assessment and monitoring are representative 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 allows for the assessment of fragmentation effects on habitat condition. Understanding these patterns is essential for developing strategies to mitigate the negative impacts of habitat fragmentation.
- **Lack of Information:** Including areas where data are lacking contributes to building a more comprehensive dataset. Selecting localities in historically under-sampled regions ensures a more balanced and complete understanding of habitat condition across its range. This helps to address data gaps and supports more informed conservation planning.
- **Accessibility and practicality:** Monitoring localities should be accessible for regular field visits, taking into account logistical factors such as distance from roads and ease of access. Practical considerations also include the safety of field personnel and the feasibility of transporting equipment to and from the site.
- **Historical data and existing monitoring sites:** Making use of existing monitoring sites with historical data can strengthen the understanding of long-term trends and changes in habitat condition. Such sites provide valuable baselines for comparison and support more robust trend analyses over time.

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

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

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

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

Sample size and distribution:

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

Sampling design:

- Within each sampling area or locality, multiple plots are established to collect detailed data on benthos, infauna, mobile species and other ecological indicators. The distribution and number of sampling stations depend on the variability and size of the habitat patch. Sampling areas (plots, transects) are laid out considering the existing main ecological gradients, e.g., exposure to waves/currents/tides, depth, sediment characteristics.

Replication and randomization:

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

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

Several initiatives and databases collect and manage glacier-related data, while another programme focuses on monitoring the biodiversity associated with glacier environments. This section provides a description of these initiatives and resources.

The **World Glacier Monitoring Service (WGMS)[9],** located in Zurich, is responsible for recording the monitoring changes in mass, volume, area and length of glaciers over time and the elaboration of inventories of glaciers, collecting information on the distribution of perennial surface ice in space. The WGMS operates as a specialized entity within a network of international scientific organizations. It functions under the umbrella of the International Association of the Cryospheric Sciences of the International Union of Geodesy and Geophysics and is affiliated with the International Science Council's World Data System. The organization's activities are endorsed and supported by several United Nations bodies, including UN Environment, UNESCO, and the World Meteorological Organization. This multi-institutional backing underscores the WGMS's significance in global cryospheric research and data management.

It is responsible for the **Global Terrestrial Network of Glaciers (GTN-G)[10]** along with the U.S. National Snow and Ice Data Centre (NSIDC) and the Global Land Ice Measurements from

[9] World Glacier Monitoring Service www.wgms.ch
[10] Global Terrestrial Network of Glaciers https://www.gtn-g.ch/

Space initiative (GLIMS). The GTN-G has eight datasets available with glacier data: glacier map collection, glacier regions, fluctuations of glaciers, World Glacier Inventory, GLIMS Inventory, Randolph Glacier Inventory, glacier photograph collection and Glacier Thickness dataset. The GTN-G follows a multi-level monitoring system across environmental gradients which results in the basic datasets required for integrative studies and assessments of the distribution and changes of glaciers and ice caps by combining in-situ, remote sensing (ASTER/GLIMS program and GIS), and numerical modelling components (2-dimensional or GIS-based spatial energy/mass balance models coupled with Atmosphere-Ocean General Circulation Models via Regional Climate Models). Currently, 94 glaciers are monitored for length change (Zemp et al., 2020). Mass balance has been recorded since 1948 (Zemp et al., 2017). Today, mass balance measurements are conducted on 10 glaciers (Zemp et al., 2020).

The **Global Glacier Change Bulletin (GGCB)** series was introduced by the WGMS in 2015, merging the former Fluctuations of Glaciers and Glacier Mass Balance Bulletin series. The GGCB provides an integrative assessment of worldwide and regional glacier changes at two-year intervals. It focuses primarily on glaciological mass balance observations, complemented by geodetic volume changes and front variation series. This new format aims to present glacier change information in a more accessible and comprehensive manner.

The **Glacial Monitoring of Switzerland (GLAMOS)**[11] is a comprehensive program aimed at studying long-term glacier changes in the Swiss Alps. It is a collaborative effort involving ETH Zurich, the University of Fribourg, and the University of Zurich, coordinated by the Swiss Academy of Sciences. GLAMOS collects data on glacier length changes for over 100 glaciers annually, measures mass balance and surface movement on selected glaciers, and determines ice volume changes for numerous glaciers every 5-10 years. The program also compiles glacier inventories and monitors firn and ice temperatures. Funded by various Swiss federal agencies, GLAMOS provides crucial information on glacier response to climate change, disseminates results to international data centers, and makes the data available to researchers and the public through reports and an online data portal.

The **Global Land Ice Measurements from Space (GLIMS)**[12] project uses satellite data to inventory glaciers worldwide, in collaboration with the NASA National Snow and Ice Data Center (NSIDC) and WGMS. It aims to enhance the World Glacier Inventory by using space-borne sensors (Zemp et al., 2007; Ohmura, 2009).

Glaciers Climate Change Initiative (Glaciers_cci) is an ESA project that uses satellite data to monitor glacier area, elevation change, and surface velocity, providing critical data for inaccessible regions (Paul et al., 2015).

With respect to glacial biodiversity, the **PrioritIce project**[13] focuses on examining the ecological dynamics of glacier-associated ecosystems across Europe. Its primary objective is to analyse the evolving patterns, potential risks, and ongoing transformations affecting the diverse life forms inhabiting glacial environments. This includes organisms thriving on the ice surface as well as those populating recently deglaciated terrains. The study places particular emphasis on regions harbouring exceptionally vulnerable glacial habitats, aiming to provide insights into the future of these unique ecological niches. The project has gathered data on the distribution

[11] Glacial Monitoring of Switzerland https://www.glamos.ch/en/#/B43-03
[12] Global Land Ice Measurements from Space https://www.glims.org
[13] https://www.biodiversa.eu/2023/04/19/prioritice/

of key taxa (bacteria, fungi, nematodes, tardigrades, earthworms, arthropods, plants), and of ecosystem functions from multiple glacial landscapes across Europe.

Concerning techniques and technology used for the monitoring, remote sensing is widely used for glacier mass balance research. Technologies like satellite gravimetry, digital elevation models, and radar are crucial for monitoring glacier changes. This method is particularly important for areas that are difficult to access (Yu et al., 2023). Distributed Mass-Balance Modelling is another approach uses numerical models to connect different observation levels and extrapolate data in space and time. It helps estimate mass balance values for unmeasured glaciers and assess special effects like dust impacts on albedo (Machguth et al., 2006). InSAR Kinematics is used for incorporating kinematic information into rock glacier inventories, this method involves spaceborne interferometric synthetic aperture radar to characterize moving areas related to rock glaciers (Bertone et al., 2022).

4 Guidelines to assess fragmentation at appropriate scales

The retreat of glaciers due to rising global temperatures has significant impacts on biodiversity and ecological services in glacial habitats.

As global temperatures continue to rise due to anthropogenic activities, the behaviour of glaciers is undergoing significant transformations. The increasing concentration of carbon dioxide and other greenhouse gases has been identified as a primary driver of these changes, leading to glacier retreat, thinning, and fragmentation. The impacts of deglaciation are often most pronounced at the terminus area, where glaciers respond to shifts in mass balance, making it essential to monitor these regions closely. These processes not only alter the physical landscape but also pose considerable risks to the biodiversity and ecological services associated with glacial habitats (Jacobsen et al., 2012; Rounce et al., 2023). Fragmentation of glaciers, particularly the detachment of tributary glaciers from main glacier bodies, can disrupt the balance of ecosystems that depend on glacial meltwater, affecting both terrestrial and aquatic environments.

An overview of drivers of glacier fragmentation is presented in Table 6.

An assessment of glacier fragmentation can be performed using change in surface velocity, thickness and frontal position (Lo Vecchio et al., 2025). Ice thickness data reveal subglacial topography and areas of thinning that contribute to glacier instability and fragmentation. Surface velocity, derived from satellite imagery through offset tracking, identifies flow patterns and changes over time linked to fragmentation processes. Terminus positions are manually mapped from satellite images to track retreat or advance, indicating physical separation between glacier sections. Combining these measurements allows a comprehensive understanding of fragmentation dynamics by linking basal conditions, ice flow behaviour, and physical disintegration of the glacier over time.

Table 6. The primary factors contributing to glacier fragmentation

Primary factor	Description
Climate change	Rising global temperatures lead to increased melting of glaciers, resulting in fragmentation.
Mass balance changes	The balance between accumulation and ablation affects glacier stability; negative mass balance leads to retreat and fragmentation.
Glacial dynamics	Internal processes, such as ice flow dynamics and structural weaknesses, contribute to fragmentation.
Hydrological changes	Altered hydrological systems can affect how water flows beneath glaciers, potentially leading to fragmentation.
Geological factors	Underlying geology and topography influence glacier behaviour; steep slopes may promote fragmentation.
Calving events	In tidewater glaciers, the calving of icebergs at the terminus leads to fragmentation and retreat.
Increased surface melt	Enhanced surface melting can weaken the glacier's structure, contributing to fragmentation.
Human activity	Anthropogenic factors can exacerbate climate change effects, indirectly influencing glacier stability.

5 Next steps to address future needs

This document provides an analysis of the methodologies used for grassland habitat monitoring in the EU Member States and compares them with the main ecological characteristics of grasslands, evaluating how well these approaches align with the requirements for effective habitat monitoring. Building upon this comparison, it proposes a common methodology for the harmonisation of habitat monitoring across the EU to improve consistency, data quality, and comparability across Member States.

These guidelines recommend standard methods for assessing and monitoring the condition of true glaciers 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, 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.

Regarding future needs of permanent glaciers, climate change poses a critical threat to the survival of glaciers, which, according to Gobbi et al. (2021), require immediate and sustained efforts that strengthen their protection:

- It is crucial to undertake a comprehensive ecological characterization of the habitat, encompassing **all glacier-related environments** such as debris-free and debris-covered glaciers, rock glaciers, proglacial zones, and glacier-fed aquatic systems, to fully understand the habitat structure and species composition.

- Monitoring programs must be specifically designed to track cold-adapted, often small and geographically isolated **species that are highly vulnerable to extinction**, including taxa that may still be undiscovered or cryptic, as their loss would be an irreversible reduction of biodiversity.
- To ensure effective conservation, future monitoring should be large-scale and coordinated, forming a **European Glacial Biodiversity Monitoring Programme** inspired by successful models like the Circumpolar Biodiversity Monitoring Programme; such programs will enable standardized data collection to detect trends over time and support adaptive management strategies.
- Importantly, monitoring efforts must integrate **socio-ecological dimensions** by considering ecosystem services essential for human well-being, including freshwater provision and recreational values, thereby guiding conservation planning in a holistic manner. The data produced through strengthened and focused monitoring will be critical for policymakers and conservation authorities to enact evidence-based protection, management, and restoration measures tailored to the unique vulnerabilities of this habitat.

Given the accelerated loss of glaciers and permafrost-related habitats, Gobbi et al. (2021) emphasize the urgency of initiating these programs promptly and maintaining long-term commitment to prevent permanent loss of biodiversity and ecosystem functions intrinsic to Habitat 8340.

In line with the statement by Gobbi et al. (2021) on the need to integrate socio-ecological dimensions and ecosystem services of permanent glaciers, further research is required to advance this field.

- **Enhanced modelling approaches:** There is a need for distributed, physically-oriented modelling studies to bridge the gap between remote sensing and specific process-focused studies. This includes using energy balance models and addressing uncertainties in temperature extrapolation and future climate scenarios (Pellicciotti et al., 2014). Simple parameterizations for glacier change in hydrological models can help assess economic impacts and predict runoff changes (Huss et al., 2010).
- **Integration of multidisciplinary research:** An integrated approach involving glaciologists, atmospheric scientists, and other experts is crucial for understanding glacier dynamics and predicting future changes (Owen et al., 2009). Expanding meteorological, hydrological, and glaciological monitoring networks is necessary for comprehensive assessments (Frenierre & Mark, 2014).

6 References

Alfaro-Sánchez, R., Martínez-Ruiz, C., Camarero, J. J., & Fernández, N. (2019). Long-lasting legacy of historical forest management on tree growth and forest structure in Mediterranean pine forests. *Forest Ecology and Management, 438*, 169–177. https://doi.org/10.1016/j.foreco.2019.01.013.

Ahn, Y., & Howat, I. M. (2011). Efficient automated glacier surface velocity measurement from repeat images using multi-image/multichip and null exclusion feature tracking. *IEEE Transactions on Geoscience and Remote Sensing, 49*(8), 2838–2846. https://doi.org/10.1109/TGRS.2011.2114891

Anesio, A. M., Lutz, S., Chrismas, N. A., & Benning, L. G. (2017). The microbiome of glaciers and ice sheets. *NPJ Biofilms and Microbiomes, 3*(1), 10. https://doi.org/10.1038/s41522-017-0019-0

Angelini, P., Casella, L., Grignetti, A., & Genovesi, P. (Eds.). (2016). *Manuali per il monitoraggio di specie e habitat di interesse comunitario (Direttiva 92/43/CEE) in Italia: Habitat* (ISPRA, Serie Manuali e linee guida, 142/2016). Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA). ISBN 978-88-448-0789-4.

Aubry-Wake, C., Baraer, M., McKenzie, J. M., Mark, B. G., Wigmore, O., Hellström, R. Å., ... & Somers, L. (2015). Measuring glacier surface temperatures with ground-based thermal infrared imaging. *Geophysical Research Letters, 42*(20), 8489–8497. https://doi.org/10.1002/2015GL065321

Bamber, J. L., & Payne, A. J. (Eds.). (2004). *Mass balance of the cryosphere: Observations and modelling of contemporary and future changes*. Cambridge University Press. ISBN 0-521-80895-2.

Barsch, D. (1996). *Rockglaciers: Indicators for the present and former geoecology in high mountain environments*. Springer. ISBN 3-540-60742-0.

BayLU (Bayerisches Landesamt für Umwelt). (2022). *Vorgaben zur Bewertung der Offenland-Lebensraumtypen (LRT) in Bayern nach Anhang I der Fauna-Flora-Habitatrichtlinie (LRT 1340 bis 8340)*. Bayerisches Landesamt für Umwelt (LfU).

Bayerische Akademie der Wissenschaften. (2021). *Bayerischer Gletscherbericht 2021 [Bavarian Glacier Report 2021]* (Machine-translated version). Bayerische Akademie der Wissenschaften, Kommission für Glaziologie.

Benn, D., & Evans, D. J. (2014). *Glaciers and glaciation*. Routledge. https://doi.org/10.4324/9780203785010

Bensettiti, F., Bioret, F., Roland, J., & Lacoste, J.-P. (Coord.). (2004). *« Cahiers d'habitats » Natura 2000. Connaissance et gestion des habitats et des espèces d'intérêt communautaire. Tome 2 – Habitats côtiers*. MEDD/MAAPAR/MNHN. Éd. La Documentation française.

Bertone, A., Barboux, C., Bodin, X., Bolch, T., Brardinoni, F., Caduff, R., ... & Strozzi, T. (2022). Incorporating InSAR kinematics into rock glacier inventories: Insights from 11 regions worldwide. *The Cryosphere, 16*(7), 2769–2792. https://doi.org/10.5194/tc-16-2769-2022

Björk, R. G., & Molau, U. (2007). Ecology of alpine snowbeds and the impact of global change. *Arctic, Antarctic, and Alpine Research, 39*(1), 34–43. https://doi.org/10.1657/1523-0430(2007)39[34:EOASAT]2.0.CO;2

Borja, A., Prins, T. C., Simboura, N., Andersen, J. H., Berg, T., Marques, J. C., ... & Uusitalo, L. (2014). Tales from a thousand and one ways to integrate marine ecosystem components when assessing the environmental status. *Frontiers in Marine Science, 1*, 72. https://doi.org/10.3389/fmars.2014.00072

Buda, J., Błażej, S., Ambrosini, R., Scotti, R., Pittino, F., Sala, D., Zawierucha, K., & Łokas, E. (2024). The surface of small glaciers as radioactive hotspots: Concentration of radioisotopes during predicted intensive melting in the Alps. *Journal of Hazardous Materials, 476*, 135083. https://doi.org/10.1016/j.jhazmat.2024.135083

Buda, J., Łokas, E., Błażej, S., Gorzkiewicz, K., Buda, K., Ambrosini, R., ... Zawierucha, K. (2023). Unveiling threats to glacier biota: Bioaccumulation, mobility, and interactions of radioisotopes with key biological components. *Chemosphere, 348*, 140738. https://doi.org/10.1016/j.chemosphere.2023.140738

Buchwald, E. (2005). A hierarchical terminology for more or less natural forests in relation to sustainable management and biodiversity conservation. In *Proceedings: Third expert meeting on harmonizing forest-related definitions for use by various stakeholders* (pp. 1–10). Food and Agriculture Organization of the United Nations.

Burrascano, S., Keeton, W. S., Sabatini, F. M., & Blasi, C. (2013). Commonality and variability in the structural attributes of moist temperate old-growth forests: A global review. *Forest Ecology and Management, 291*, 458–479. https://doi.org/10.1016/j.foreco.2012.11.020

Callaghan, T. V., Björn, L. O., Chapin, F. S. III, Chernov, Y., Christensen, T. R., Huntley, B., Ims, R., Johansson, M., Riedlinger, D. J., & Jonasson, S. (2005). Arctic tundra and polar desert ecosystems. In *Arctic Climate Impact Assessment* (Vol. 1, pp. 243–352). Cambridge University Press. https://durham-repository.worktribe.com/output/1692707

Callaghan, T. V., & Johansson, M. (2015). Snow, ice and the biosphere. In J. F. Shroder, W. Haeberli, & C. Whiteman (Eds.), *Snow and ice-related hazards, risks, and disasters* (pp. 139–165). Academic Press. https://doi.org/10.1016/B978-0-12-394849-6.00005-6

Cannone, N., Diolaiuti, G., Guglielmin, M., & Smiraglia, C. (2008). Accelerating climate change impacts on alpine glacier forefield ecosystems in the European Alps. *Ecological Applications, 18*(3), 637–648. http://www.jstor.org/stable/40062174

Cauvy-Fraunié, S., & Dangles, O. (2019). A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution, 3*, 1675–1685. https://doi.org/10.1038/s41559-019-1042-8

Chifflard, P., Boodoo, K. S., Ditzel, L., Reiss, M., & Fasching, C. (2024). Icelandic glacial dissolved organic carbon fluxes, composition and variability – relevance for the global glacial carbon budget. *Science of The Total Environment, 957*, 177366. https://doi.org/10.1016/j.scitotenv.2024.177366

Christner, B. C., Priscu, J. C., Achberger, A. M., Barbante, C., Carter, S. P., Christianson, K., ... Vick-Majors, T. J. (2014). A microbial ecosystem beneath the West Antarctic ice sheet. *Nature, 512*(7514), 310–313. https://doi.org/10.1038/nature13667

CIS (Common Implementation Strategy, ECOSTAT Working Group). (2003). *Overall approach to the classification of ecological status and ecological potential*. Water Framework Directive Common Implementation Strategy Working Group 2A, Ecological Status (ECOSTAT), Rome.

Crosta, A., Valle, B., Caccianiga, M., Gobbi, M., Ficetola, F. G., Pittino, F., ... & Ambrosini, R. (2025). Ecological interactions in glacier environments: A review of studies on a model Alpine glacier. *Biological Reviews, 100*(1), 227–244. https://doi.org/10.1111/brv.13138

Cogley, J. G. (2010). Mass-balance terms revisited. *Journal of Glaciology, 56*(200), 997–1001. https://doi.org/10.3189/002214311796406040

Cook, J. M., Hodson, A. J., Taggart, A. J., Mernild, S. H., Tranter, M., Irvine-Fynn, T., ... & Yallop, M. L. (2016). Cryoconite: The dark biological secret of the cryosphere. *Progress in Physical Geography, 40*(1), 66–111. https://doi.org/10.1177/0309133315616574

Czúcz, B., Keith, H., Maes, J., Driver, A., Jackson, B., Nicholson, E., ... & Obst, C. (2021). Selection criteria for ecosystem condition indicators. *Ecological Indicators, 133*, 108376. https://doi.org/10.1016/j.ecolind.2021.108376

Dimopoulos, P., Tsiripidis, I., Xystrakis, F., Kallimanis, A., & Panitsa, M. (2018). *Methodology for monitoring and conservation status assessment of the habitat types in Greece*. National Center of the Environment and Sustainable Development, 128 pp. Athens.

Dubnick, A., Barker, J., Sharp, M., Wadham, J., Lis, G., Telling, J., ... & Jackson, M. (2010). Characterization of dissolved organic matter (DOM) from glacial environments using total fluorescence spectroscopy and parallel factor analysis. *Annals of Glaciology, 51*(56), 111–122. https://doi.org/10.3189/172756411795931912

Dugdale, R. (1972). A statistical analysis of some measures of the state of a glacier's "Health". *Journal of Glaciology, 11*, 73–79. https://doi.org/10.3189/S0022143000022516

Ellwanger, G., Runge, S., Wagner, M., Ackermann, W., Neukirchen, M., Frederking, W., Müller, C., Ssymank, A., & Sukopp, U. (2018). Current status of habitat monitoring in the European Union according to Article 17 of the Habitats Directive, with an emphasis on habitat structure and functions and on Germany. *Nature Conservation, 29*, 57–78. https://doi.org/10.3897/natureconservation.29.27273

Ellmauer, T. (Hrsg.). (2005). *Entwicklung von Kriterien, Indikatoren und Schwellenwerten zur Beurteilung des Erhaltungszustandes der Natura 2000-Schutzgüter. Band 3: Lebensraumtypen des Anhangs I der Fauna-Flora-Habitat-Richtlinie*. Im Auftrag der neun österreichischen Bundesländer, des Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft und der Umweltbundesamt GmbH, 616 S..

European Commission, DG Environment. (2013). *Interpretation manual of European Union habitats - EUR 28*. Brussels: European Commission.

European Commission. (2023). *Reporting under Article 17 of the Habitats Directive: Guidelines on concepts and definitions – Article 17 of Directive 92/43/EEC, Reporting period 2019-2024*. DG Environment. Brussels. 104 pp.

Frenierre, J., & Mark, B. (2014). A review of methods for estimating the contribution of glacial meltwater to total watershed discharge. *Progress in Physical Geography, 38*, 173–200. https://doi.org/10.1177/0309133313516161

Geissler, J., Mayer, C., Jubanski, J., Münzer, U., & Siegert, F. (2021). Analyzing glacier retreat and mass balances using aerial and UAV photogrammetry in the Ötztal Alps, Austria. *The Cryosphere, 15*, 3699–3717. https://doi.org/10.5194/tc-15-3699-2021

Giardino, J. R., & Vitek, J. D. (1988). The significance of rock glaciers in the glacial-periglacial landscape continuum. *Journal of Quaternary Science, 3*(1), 97–103. https://doi.org/10.1002/jqs.3390030111

Gobbi, M., Ambrosini, R., Casarotto, C., Diolaiuti, G., Ficetola, G., Lencioni, V., Seppi, R., Smiraglia, C., Tampucci, D., Valle, B., & Caccianiga, M. (2021). Vanishing permanent glaciers: Climate change is threatening a European Union habitat (Code 8340) and its poorly known biodiversity. *Biodiversity and Conservation, 30*, 2257–2276. https://doi.org/10.1007/s10531-021-02185-9

Gök, D. T., Scherler, D., & Wulf, H. (2024). Land surface temperature trends derived from Landsat imagery in the Swiss Alps. *The Cryosphere, 18*, 5259–5276. https://doi.org/10.5194/tc-18-5259-2024

Greve, R., & Blatter, H. (2009). *Dynamics of ice sheets and glaciers*. Springer Science & Business Media. https://doi.org/10.3189/002214311798043717

Hock, R., & Huss, M. (2021). Glaciers and climate change. In T. M. Letcher (Ed.), *Climate Change* (pp. 157–176). Elsevier. https://doi.org/10.1016/B978-0-12-821575-3.00009-8

Hoham, R. W., & Remias, D. (2019). Snow and glacial algae: A review. *Journal of Phycology, 51*(2), 264–282. https://doi.org/10.1111/jpy.12952

Hotaling, S., Hood, E., & Hamilton, T. L. (2017). Microbial ecology of mountain glacier ecosystems: Biodiversity, ecological connections and implications of a warming climate. *Environmental Microbiology, 19*(8), 2935–2948. https://doi.org/10.1111/1462-2920.13766

Huss, M., Jouvet, G., Farinotti, D., & Bauder, A. (2010). Future high-mountain hydrology: A new parameterization of glacier retreat. *Hydrology and Earth System Sciences, 14*, 815–829. https://doi.org/10.5194/hess-14-815-2010

Jacobsen, D., Milner, A., Brown, L., & Dangles, O. (2012). Biodiversity under threat in glacier-fed river systems. *Nature Climate Change, 2*, 361–364. https://doi.org/10.1038/nclimate1435

Jakobsson, S., Töpper, J. P., Evju, M., Framstad, E., Lyngstad, A., Pedersen, B., ... & Nybø, S. (2020). Setting reference levels and limits for good ecological condition in terrestrial ecosystems–Insights from a case study based on the IBECA approach. *Ecological Indicators, 116*, 106492. https://doi.org/10.1016/j.ecolind.2020.106492

Jaroměřská, T. N., Ambrosini, R., Mazurkiewicz, M., Franlti, A., Klimaszyk, P., Rozwalak, P., ... & Zawierucha, K. (2023). Spatial distribution and stable isotopic composition of invertebrates uncover differences between habitats on the glacier surface in the Alps. *Limnology, 24*(2), 83–93. https://dx.doi.org/10.1007/s10201-023-00713-w

Ji, Q., Yang, T., He, Y., Qin, Y., Dong, J., & Hu, F. (2017). A simple method to extract glacier length based on Digital Elevation Model and glacier boundaries for simple basin type glacier. *Journal of Mountain Science, 14*, 1–10. https://doi.org/10.1007/s11629-016-4243-5

Karpilo, R. D., Jr. (2009). Glacier monitoring techniques. In R. Young & L. Norby (Eds.), *Geological Monitoring* (pp. 141–162). Geological Society of America. https://www.nps.gov/articles/glacier-monitoring-techniques.htm

Keith, H., Czúcz, B., Jackson, B., Driver, A., Nicholson, E., & Maes, J. (2020). A conceptual framework and practical structure for implementing ecosystem condition accounts. *One Ecosystem, 5*, e58216. https://doi.org/10.3897/oneeco.5.e58216

Khelidj, N., Caccianiga, M., Cerabolini, B., Tampucci, D., & Losapio, G. (2024). Glacier extinction homogenizes functional diversity via ecological succession. *Journal of Vegetation Science*. https://doi.org/10.1111/jvs.13312

Kozioł, K., Moggridge, H., Cook, J., & Hodson, A. (2018). Organic carbon fluxes of a glacier surface: A case study of Foxfonna, a small Arctic glacier. *Earth Surface Processes and Landforms, 44*(2), 405–416. https://doi.org/10.1002/esp.4501

Kurzböck, C., & Huss, M. (2021). Measurement, documentation and evaluation of glacier monitoring data. *GLAMOS, ETH Zurich, Switzerland*.

Langhans, S. D., Reichert, P., & Schuwirth, N. (2014). The method matters: A guide for indicator aggregation in ecological assessments. *Ecological Indicators, 45*, 494–507. https://doi.org/10.1016/j.ecolind.2014.05.014

Lieb, G. K., & Kellerer-Pirklbauer, A. (2021). *Length changes of Austrian glaciers in 2019/2020* [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.933015

Lo Vecchio, A., Villalba, R., Falaschi, D., Ruiz, L., Vacaflor, P., & Vargas, S. (2025). Glacier fragmentation on the Southern Patagonian Icefield: A comprehensive analysis of the Upsala Glacier. *Journal of Glaciology, 71*, e16, 1–12.

https://doi.org/10.1017/jog.2024.91

Lutz, S., Anesio, A., Edwards, A., & Benning, L. (2015). Microbial diversity on Icelandic glaciers and ice caps. *Frontiers in Microbiology, 6*, Article 307. https://doi.org/10.3389/fmicb.2015.00307

Lutz, S., Anesio, A. M., Edwards, A., & Benning, L. G. (2017). Linking microbial diversity and functionality of arctic glacial surface habitats. *Environmental Microbiology, 19*(2), 551–565. https://doi.org/10.1111/1462-2920.13494

Maccario, L., Carpenter, S. D., Deming, J. W., Vogel, T. M., & Larose, C. (2019). Sources and selection of snow-specific microbial communities in a Greenlandic sea ice snow cover. *Scientific Reports, 9*(1), 2290. https://doi.org/10.1038/s41598-019-38744-y

Machguth, H., Paul, F., Hoelzle, M., & Haeberli, W. (2006). Distributed glacier mass-balance modelling as an important component of modern multi-level glacier monitoring. *Annals of Glaciology, 43*, 335–343. https://doi.org/10.3189/172756406781812285

Maciejewski, L. (2010). Méthodologie d'élaboration des listes d'« espèces typiques » pour des habitats forestiers d'intérêt communautaire en vue de l'évaluation de leur état de conservation. Rapport SPN 2010-12 / MNHN-SPN, Paris, 48 p. + annexes.

Makowska-Zawierucha, N., Mokracka, J., Małecka, M., & Małek, W. (2022). Quantification of class 1 integrons and characterization of the associated gene cassettes in the high Arctic – Interplay of humans and glaciers in shaping the aquatic resistome. *Ecological Indicators, 145*, 109633. https://doi.org/10.1016/j.ecolind.2022.109633

Milner, A., Brown, L., & Hannah, D. (2009). Hydroecological response of river systems to shrinking glaciers. *Hydrological Processes, 23*, 62–77. https://doi.org/10.1002/hyp.7197

Montagna, M., Urbanelli, S., & Rossaro, B. (2016). The species of the genus Diamesa (Diptera, Chironomidae) known to occur in Italian Alps and Apennines. *Zootaxa, 4193*(2), 317–331. https://doi.org/10.11646/zootaxa.4193.2.7

Naturvårdsverket. (2011). Vägledning för svenska naturtyper i habitatdirektivets bilaga 1: Glaciärer, permanenta glaciärer (Permanent glaciers) (Report No. NV-04493-11). Retrieved from https://www.naturvardsverket.se/4ac1c9/contentassets/f3bef5a94c1b4a9b968c33ecb64d281e/vl_8340_glaciarer.pdf

Nijhawan, R., & Jain, K. (2018, April). Glacier terminus position monitoring and modelling using remote sensing data. In *International Conference on Advances in Computing and Data Sciences* (pp. 11–23). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-13-1813-9_2

Ohmura, A. (2009). Completing the World Glacier Inventory. *Annals of Glaciology, 50*, 148–154. https://doi.org/10.3189/172756410790595840

Owen, L., Thackray, G., Anderson, R., Briner, J., Kaufman, D., Roe, G., Pfeffer, W., & Yi, C. (2009). Integrated research on mountain glaciers: Current status, priorities and future prospects. *Geomorphology, 103*, 158–171. https://doi.org/10.1016/J.GEOMORPH.2008.04.019

Paul, F., Bolch, T., Kääb, A., Nagler, T., Nuth, C., Scharrer, K., Shepherd, A., Strozzi, T., Ticconi, F., Bhambri, R., Berthier, E., Bevan, S., Gourmelen, N., Heid, T., Jeong, S., Kunz, M., Lauknes, T. R., Luckman, A., Merryman Boncori, J. P., Moholdt, G., Muir, A., Neelmeijer, J., Rankl, M., VanLooy, J., & Van Niel, T. (2015). The glaciers climate change initiative: Methods for creating glacier area, elevation change and velocity products. *Remote Sensing of Environment, 162*, 408–426. https://doi.org/10.1016/j.rse.2013.07.043

Pellicciotti, F., Ragettli, S., Carenzo, M., & McPhee, J. (2014). Changes of glaciers in the Andes of Chile and priorities for future work. *Science of the Total Environment, 493*, 1197–1210. https://doi.org/10.1016/j.scitotenv.2013.10.055

Pescador, D. S., Vayreda, J., Escudero, A., & Lloret, F. (2022). El potencial del Inventario Forestal Nacional para evaluar el estado de conservación de los tipos de Hábitat forestales de Interés Comunitario: nuevos retos para cumplir con las políticas de conservación de la biodiversidad. *Ecosistemas, 31*(3), 2384. https://doi.org/10.7818/ECOS.2384

Price, P. B., Nagornov, O. V., Bay, R., Chirkin, D., He, Y., Miocinovic, P., Richards, A., Woschnagg, K., Koci, B., & Zagorodnov, V. (2002). Temperature profile for glacial ice at the South Pole: Implications for life in a nearby subglacial lake. *Proceedings of the National Academy of Sciences of the United States of America, 99*(12), 7844–7847. https://doi.org/10.1073/pnas.082238999

Remias, D., Karsten, U., Lütz, C., & Leya, T. (2010). Physiological and morphological processes in the Alpine snow alga *Chloromonas nivalis* (Chlorophyceae) during cyst formation. *Protoplasma, 243*, 73–86. https://doi.org/10.1007/s00709-010-0123-y

Robbins, E., Breininger, R. D., Jiang, M., Madera, M., White, R. T., & Kachouie, N. N. (2024). Segmentation of glacier area using U-Net through Landsat satellite imagery for quantification of glacier recession and its impact on marine systems. *Journal of Marine Science and Engineering, 12*(10), 1788. https://doi.org/10.3390/jmse12101788

Rosvold, J. (2016). Perennial ice and snow-covered land as important ecosystems for birds and mammals. *Journal of Biogeography, 43*(1), 3–12. https://doi.org/10.1111/jbi.12609

Rounce, D., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L., Copland, L., Farinotti, D., Menounos, B., & McNabb, R. (2023). Global glacier change in the 21st century: Every increase in temperature matters. *Science, 379*, 83–88. https://doi.org/10.1126/science.abo1324

Rozwalak, P., Podkowa, P., Buda, J., Niedzielski, P., Kawecki, S., Ambrosini, R., Azzoni, R., Baccolo, G., Ceballos, J., Cook, J., Di Mauro, B., Ficetola, G. F., Franzetti, A., Ignatiuk, D., Klimaszyk, P., Łokas, E., Ono, M., Parnikoza, I., Pietryka, M., & Zawierucha, K. (2022). Cryoconite – From minerals and organic matter to bioengineered sediments on glacier's surfaces. *Science of The Total Environment, 150874*. https://doi.org/10.1016/j.scitotenv.2021.150874

Sabatini, F. M., Burrascano, S., Keeton, W. S., Levers, C., Lindner, M., Pötzschner, F., ... & Kuemmerle, T. (2018). Where are Europe's last primary forests? *Diversity and Distributions, 24*(10), 1426–1439. https://doi.org/10.1111/ddi.12778

Stibal, M., Bradley, J. A., Edwards, A., Hotaling, S., Zawierucha, K., Rosvold, J., ... & Anesio, A. M. (2020). Glacial ecosystems are essential to understanding biodiversity responses to glacier retreat. *Nature Ecology & Evolution, 4*(5), 686–687. https://doi.org/10.1038/s41559-020-1163-0

Stibal, M., Šabacká, M., & Žárský, J. (2012). Biological processes on glacier and ice sheet surfaces. *Nature Geoscience, 5*(11), 771–774. https://doi.org/10.1038/ngeo1611

Soranno, P. A., Wagner, T., Martin, S. L., McLean, C., Novitski, L. N., Provence, C. D., & Rober, A. R. (2011). Quantifying regional reference conditions for freshwater ecosystem management: A comparison of approaches and future research needs. *Lake and Reservoir Management, 27*(2), 138–148. https://doi.org/10.1080/07438141.2011.573614

Stoddard, J. L., Larsen, D. P., Hawkins, C. P., Johnson, R. K., & Norris, R. H. (2006). Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications, 16*(4), 1267–1276. https://doi.org/10.1890/1051-0761(2006)016[1267:SEFTEC]2.0.CO;2[1]

Storch, F., Dormann, C. F., & Bauhus, J. (2018). Quantifying forest structural diversity based on large-scale inventory data: a new approach to support biodiversity monitoring. *Forest Ecosystems, 5*(1), 1–14. https://doi.org/10.1186/s40663-018-0151-1

Tampucci, D., Boffa, G., Mangili, F., Gobbi, M., & Caccianiga, M. (2015). Vegetation outlines of two active rock glaciers with contrasting lithology. *Plant Sociology, 52*(1), 9–18. https://doi.org/10.7338/PLS2015521/02

Tampucci, D., Gobbi, M., Marano, G., Boracchi, P., Boffa, G., Ballarin, F., ... & Caccianiga, M. (2017). Ecology of active rock glaciers and surrounding landforms: climate, soil, plants and arthropods. *Boreas, 46*(2), 185–198. https://doi.org/10.1111/bor.12219

Tranter, M., Skidmore, M., & Wadham, J. (2005). Hydrological controls on microbial communities in subglacial environments. *Hydrological Processes, 19*(4), 995–998. https://doi.org/10.1002/hyp.5854

Triglav-Čekada, M., & Gabrovec, M. (2013). Documentation of Triglav glacier, Slovenia, using non-metric panoramic images. *Annals of Glaciology, 54*(62), 80–86. https://doi.org/10.3189/2013AoG62A095

United Nations. (2021). System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA). White cover publication, pre-edited text subject to official editing. Available at: https://seea.un.org/ecosystem-accounting

Valle, B., Ambrosini, R., Caccianiga, M., & Gobbi, M. (2020). Ecology of the cold-adapted species Nebria germari (Coleoptera: Carabidae): the role of supraglacial stony debris as refugium during the current interglacial period. *Acta Zoologica Academiae Scientiarum Hungaricae, 66*, 199–220. https://doi.org/10.17109/AZH.66.Suppl.199.2020

Valle, B., Ligi, O., Moscatelli, A., Onelli, E., & Caccianiga, M. (2025). Bryophyte colonisation on recently deglaciated lands in the European Alps. *Journal of Bryology, 47*(1), 44–54. https://doi.org/10.1080/03736687.2025.2456310

Vallecillo Rodriguez, S., Maes, J., Teller, A., Babí Almenar, J., Barredo Cano, J. I., Paracchini, M. C. A., ... & Gumbert, A. (2022). EU-wide methodology to map and assess ecosystem condition. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/13048

Varliero, G., Holland, A., & Anesio, A. M. (2021). Glacier clear ice bands indicate englacial channel microbial distribution. Journal of Glaciology, 67(261), 1090–1104. https://doi.org/10.1017/jog.2021.30

Varotto, C., Pindo, M., Bertoni, E., et al. (2021). A pilot study of eDNA metabarcoding to estimate plant biodiversity by an alpine glacier core (Adamello glacier, North Italy). Scientific Reports, 11, 1208. https://doi.org/10.1038/s41598-020-79738-5

Wang, T., Zhang, Z., Liu, L., Li, Z., Wang, P., Xu, L., Zhao, G., Tian, H., Kang, Z., Chen, H., & Zhang, X. (2021). Simulation of the Potential Distribution of the Glacier Based on Maximum Entropy Model in the Tianshan Mountains, China. *Water*, 13, 1541. https://doi.org/10.3390/W13111541

Williamson, C. J., Cameron, K. A., Cook, J. M., Zarsky, J. D., Stibal, M., Edwards, A., ... & Anesio, A. M. (2019). Glacier algae: A dark past and a darker future. *Frontiers in Microbiology, 10*, 524. https://doi.org/10.3389/fmicb.2019.00524

Webster, M. A., Gerland, S., Holland, M., Hunke, E., Kwok, R., Lecomte, O., et al. (2018). Snow in the changing sea-ice systems. *Nature Climate Change, 8*, 946–953. https://doi.org/10.1038/s41558-018-0286-7

Wejnerowski, Ł., Poniecka, E., Buda, J., Klimaszyk, P., Piasecka, A., Dziuba, M. K., ... Zawierucha, K. (2023). Empirical testing of cryoconite granulation: Role of cyanobacteria in the formation of key biogenic structure darkening glaciers in polar regions. *Journal of Phycology, 59*(5), 939–949. https://doi.org/10.1111/jpy.13372

Welty, E., Zemp, M., Navarro, F., Huss, M., Fürst, J. J., Gärtner-Roer, I., Landmann, J., Machguth, H., Naegeli, K., Andreassen, L. M., Farinotti, D., Li, H., & GlaThiDa Contributors. (2020). Worldwide version-controlled database of glacier thickness observations. *Earth System Science Data, 12*, 3039–3055. https://doi.org/10.5194/essd-12-3039-2020

Wirth, C., Messier, C., Bergeron, Y., Frank, D., & Fankhänel, A. (2009). Old-growth forest definitions: A pragmatic view. In C. Wirth, G. Gleixner, & M. Heimann (Eds.), *Old-growth forests: Function, fate and value* (pp. 11–33). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-92706-8_2

Yu, A., Shi, H., Wang, Y., Yang, J., Gao, C., & Lu, Y. (2023). A bibliometric and visualized analysis of remote sensing methods for glacier mass balance research. *Remote Sensing, 15*(5), 1425. https://doi.org/10.3390/rs15051425

Zangrando, R., Zanella, V., Karroca, O., Barbaro, E., Kehrwald, N. M., Battistel, D., ... Barbante, C. (2020). Dissolved organic matter in the deep TALDICE ice core: A nano-UPLC-nano-ESI-HRMS method. *Science of The Total Environment, 700*, 134432. https://doi.org/10.1016/j.scitotenv.2019.134432

Zawierucha, K., Kolicka, M., Takeuchi, N., & Kaczmarek, Ł. (2015). What animals can live in cryoconite holes? *Journal of Zoology, 295*(3), 159–169. https://doi.org/10.1111/jzo.12195

Zemp, M., Amstrong, R., Haeberli, W., Hoelzle, M., Kääb, A., Kargel, J., ... Raup, B. H. (2007). Worldwide glacier monitoring–present state and current challenges. *Ice and Climate News: The WCRP/SCAR Climate and Cryosphere Newsletter, 2007*(9), 4. https://doi.org/10.5167/uzh-33355

Zemp, M., Nussbaumer, S. U., Gärtner-Roer, I., Huber, J., Machguth, H., Paul, F., & Hoelzle, M. (Eds.). (2017). *Global Glacier Change Bulletin No. 2 (2014–2015)*. ICSU(WDS) / IUGG(IACS) / UNEP / UNESCO / WMO. World Glacier Monitoring Service. Zurich, Switzerland. 244 pp. https://doi.org/10.5904/wgms-fog-2017-10

Zemp, M., Gärtner-Roer, I., Nussbaumer, S. U., Bannwart, J., Rastner, P., Paul, F., & Hoelzle, M. (Eds.). (2020). *Global Glacier Change Bulletin No. 3 (2016–2017)*. ISC(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO. World Glacier Monitoring Service, Zurich, Switzerland. 274 pp. https://doi.org/10.5904/wgms-fog-2019-12

Getting in touch with the EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

– by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),
– at the following standard number: +32 22999696,
– via the following form: european-union.europa.eu/contact-eu/write-us_en.

Finding information about the EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

EU open data

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

KH-01-25-207-EN-N

Publications Office
of the European Union