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Brief communication: Cryosphere ecosystem services and disservices are transforming glaciology into a multidisciplinary research nexus

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Abstract. Glaciology is evolving from a physical science research discipline focused on the properties and processes of ice and snow into a multidisciplinary research nexus. The rapid transformation of the cryosphere is also shaping the ecosystem services and disservices (ESD) it provides, connecting glacial processes to freshwater security, natural hazards, biodiversity, economics, and cultural values. Integrating ESD within glaciology provides a unifying conceptual language across the environmental sciences, ecology, social sciences, humanities, and governance. This shift is redefining glaciologists as cryospheric system scientists who combine biophysical data with socio-ecological impacts to address the challenges of climate and environmental change.

1 Introduction

Since the origin of modern glaciology in the early-to-mid 19th century, when scientists began to systematically observe and analyse glacial systems (Clarke, 1987), glaciology has traditionally focused on the physical properties and processes of glacier ice and snow. Glacier mass balance, ice dynamics, glacier-climate interactions, and glacial hydrology have formed the core of a discipline largely rooted in the Earth and environmental sciences. Over recent decades, however, the rapid loss and transformation of the cryosphere under climate change have progressively expanded the scope of glaciological research. The retreat of glaciers and decline of the wider cryosphere are now studied not only to understand their response to climate forcing, but also to address current and emerging issues such as freshwater availability, emergence of novel ecosystems, hazards, biodiversity loss, landscape evolution, tourism pressures, and human livelihoods (IPCC, 2019; Immerzeel et al., 2020; Gaudio & Gobbi, 2022, Clason et al., 2023).

This expansion in scope is particularly evident in emerging literature on the ecosystem services and disservices provided by the cryosphere (hereafter ESD). Glacial and other terrestrial ice can contribute to freshwater provision, hydrological regulation, food and energy production, recreation, tourism, education, cultural identity, and climate refugia for species in polar and alpine environments, while simultaneously generating or compounding risks from glacier-related hazards such as glacier lake outburst floods and glacier collapses (Cook et al., 2021; Gaudio & Gobbi, 2022; Malinauskaite et al., 2025). Recent reviews have drawn attention to the large diversity of ESD related to the cryosphere, with regulating and

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maintenance services such as drought prevention, water storage, and biogeochemical cycling dominating within current glaciological research (Malinauskaite et al., 2025; Filippelli et al., 2026).

Here, we argue that this expansion in the scope of glaciological research has implications beyond the identification and evaluation of individual ESD, and that the integration of the ESD perspective within the discipline is contributing to a conceptual transformation of glaciology itself. Explicitly connecting cryospheric processes to ecosystem functions, human benefits, values, and risk creates a research nexus in which the Earth and environmental sciences interact with ecology, biology, economics, social sciences, humanities, and governance. In this sense, ESD provide not only a new application for glaciology, but a common conceptual language through which previously disparate and siloed research traditions can be integrated.

2 From glaciers as physical systems to the cryosphere as socio-environmental provider

The cryosphere interacts with both biological and human systems, and its physical processes, particularly meltwater generation, can generate outputs that contribute directly or indirectly to human wellbeing. The importance of these contributions is strongly dependent on spatial and temporal context: mountain regions act as “water towers” for downstream ecosystems and communities, and glacier runoff can buffer seasonal water shortages, although this contribution will decline in the near-to-medium term with continued glacier mass loss (Immerzeel et al., 2020; Huss and Hock, 2018; Clason et al., 2023a). Thus, a conventional glaciological variable such as mass balance becomes connected to questions of water supply, food security, and energy generation.

The same logic applies to ecological processes. Glaciers and glacier-fed streams are not biologically empty environments. They host specialized communities (Simoncini et al., 2026) and exert influence on downstream aquatic and terrestrial ecosystems at daily, seasonal, and long-term timescales. Changes in glacier cover can therefore alter habitat availability, community composition, and ecosystem functioning (Milner et al., 2017; Losapio et al., 2025; Ficetola et al., 2024). Glacier retreat consequently represents not only a change in ice volume or area, but also a transition between ecological states, with associated consequences for the people reliant upon these ecosystems for economic livelihood or subsistence.

The cultural contributions of glaciers are another key example. Glacial landscapes have recreational, aesthetic, educational, spiritual, and identity-related values that cannot be inferred from physical measurements alone. Their assessment requires approaches capable of integrating biophysical observations with social perceptions and culturally specific values (Zimmer et al., 2022; Varutti et al., 2025). The broader concept of ‘Nature's Contributions to People’, developed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, is particularly relevant in this context because it recognizes diverse relationships between people and nature, including cultural values and different knowledge systems (Díaz et al., 2018).

There is, therefore, a key conceptual shift in how we study glaciers; from asking ‘how do glaciers behave physically?’, to asking ‘how do cryospheric processes contribute to ecological functioning and human well-being?’. The first question

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remains fundamental to the discipline of glaciology, but the second substantially expands the scientific space in which glaciology operates.

3 Ecosystem services and disservices (ESD) as a multidisciplinary research nexus

The ESD perspective establishes a conceptual cascade from the physical presence and processes of the cryosphere to its ecosystem functions, services, benefits, and values. This cascade creates a research interface with several disciplines that were historically peripheral to glaciology.

Perhaps the most established existing intersection is with hydrology, where quantifying glacier storage and runoff is essential for understanding freshwater provision, seasonality, and downstream vulnerability (Huss and Hock, 2018). However, assessing the societal significance of changes in the provisioning and regulating services provided by meltwater also requires knowledge of water demand, infrastructure, governance, and socioeconomic vulnerability. Glaciological modelling alone cannot determine whether a change in runoff constitutes a loss of a service, a redistribution of a service, or an opportunity for adaptation.

There are also increasing links between glaciology and ecology. Glacier retreat reorganizes physical habitats, sediment fluxes, water temperature, nutrient dynamics, and species interactions, thereby influencing biodiversity and ecosystem functioning (Milner et al., 2017; Losapio et al., 2025; Ficetola et al., 2025). This creates a direct connection between the study of glacier mass loss and ecological research. Increasingly, the glacier itself becomes one component of a coupled glacier-river-terrestrial/marine ecosystem rather than an isolated physical object. Biogeochemistry provides a further bridge between disciplines. Glacier retreat and the emergence of ice-free areas, and novel ecosystems, after deglaciation influence the transport and transformation of carbon, nutrients, and other chemical constituents, including emerging contaminants like pesticides, micro- and nanoplastics, and legacy materials like fallout radionuclides (Beard et al., 2022; Clason et al., 2023b). Thus, understanding the consequences of cryosphere change requires interactions between glaciology and many other physical and natural science disciplines, such as geomorphology, hydrology, soil science, ecology, microbiology, and biogeochemistry.

This emerging research nexus also extends beyond the natural sciences. ESD are ultimately linked to people, and their assessment therefore involves economics, human geography, anthropology, political science, and environmental governance. Cook et al. (2021), for example, emphasized that several glacier ESD are co-produced: physical glacier processes create potential services, but infrastructure, institutions, markets, and cultural practices determine how those services are mobilized and appropriated. A glacier may provide meltwater, but whether that water is ultimately used for drinking water, agriculture, or hydropower depends on human systems, environment-society physical connectivity, and downstream demand. This is particularly important under rapid climate change and the associated consequences for changing resource security. The loss of a glacier may simultaneously lead to a reduction or loss of some socio-environmental contributions while increasing others. Declining ice volume will reduce long-term glacier contribution to freshwater, but newly exposed terrain can increase

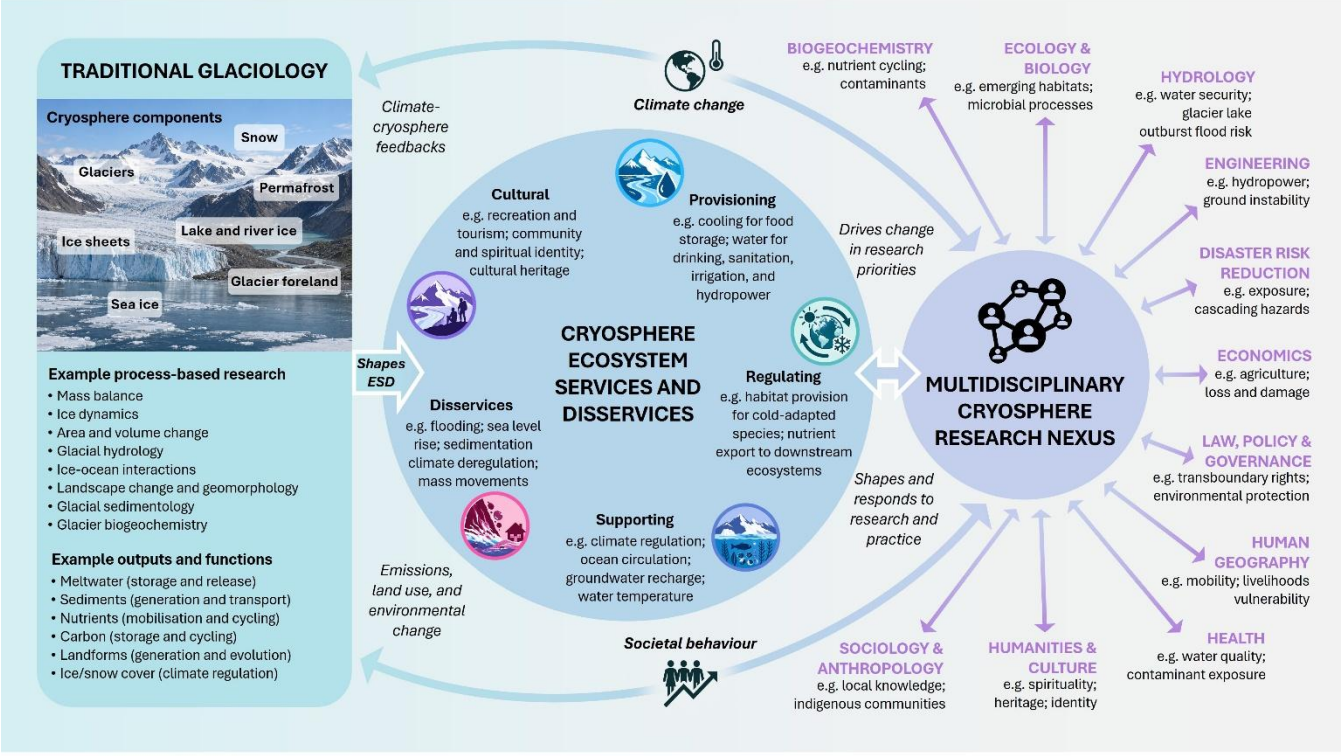
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habitat availability during the early stages of deglaciation (Zimmer et al., 2022; Ficetola et al. 2024). Similarly, glacier retreat may reduce opportunities for glacier-based tourism while creating new recreational landscapes.

The cryosphere also produces significant disservices, comprising natural processes, properties, or hazards originating from snow, ice, glaciers, sea ice, lake and river ice, and permafrost that negatively impact human well-being, safety, health, and economic activities (Cook et al., 2021). In mountain environments such as the European Alps and Himalaya glacier-related hazards pose acute risks. Catastrophic ice avalanches and glacial lake outburst floods, such as the 2022 Marmolada glacier collapse in Italy or the 2026 Nepal debris avalanche and flash flood, threaten both downstream indigenous communities and infrastructure. At the same time, degrading permafrost is undermining high-altitude infrastructure, causing ground instability, rockfalls, and cable car foundation failures across the Alps, while Arctic permafrost thaw damages roads, pipelines, and housing. Furthermore, melting glaciers and thawing permafrost remobilize locked-up contaminants, including persistent organic pollutants, heavy metals, and dormant biological agents, deteriorating freshwater quality in alpine catchments (Beard et al., 2022; Clason et al., 2023). Beyond land ice, unpredictable sea ice drift and coastal ice degradation compromise indigenous transport routes and maritime safety in polar regions.

Recent syntheses have emphasized that cryospheric change can produce both ecosystem services and disservices, whose magnitude, distribution, and socio-environmental significance vary both spatially and temporally (Malinauskaite et al., 2025). Ecosystem services and disservices must be jointly considered within research of cryosphere elements and their socio-economic roles, as both will evolve under climate and environmental change. The integration of glaciology with disciplines such as risk management, environmental law, and policy is particularly important if cryospheric loss and damage is to be better considered within climate litigation and reparations (Huggel et al., 2019). The multidisciplinary cryosphere research nexus emerging from these increasingly common disciplinary interactions is thus better represented as a network than as a linear chain (Fig. 1).

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120 **Figure 1.** Conceptual representation of the evolution from process-based glaciology to an integrated cryosphere research nexus. Cryospheric processes generate physical and ecological functions that contribute to provisioning, regulating, cultural, and supporting services, in addition to disservices. These (dis)services interact with human infrastructure, institutions, markets, knowledge systems, and values to generate both benefits and risks, requiring a multidisciplinary research approach. Ecosystem services and disservices thus constitute a conceptual bridge between cryospheric processes, ecosystems, and
125 society, rather than a separate research domain.

4 What changes for glaciology?

Recognizing the cryosphere as a provider of ESD presents opportunities to change or expand upon glaciological research in at least three fundamental ways.

First, it changes the objects of measurement. Traditional glaciological observations focus on variables such as glacier area,
130 thickness, velocity, mass balance, and runoff. A nexus approach retains these measurements but adds indicators such as ecosystem condition, biodiversity, water demand, economic value, cultural significance, and societal vulnerability. The result is not a replacement of physical observations but their integration into a broader network of evidence.

Second, it expands the spatial scale of analysis. A glacier is a local physical system, but the services associated with it can extend for hundreds or thousands of kilometres downstream, while simultaneously any disservices (such as slope instability)

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could be present for years, decades, or longer. Conversely, the value attributed to a glacier may depend on communities, infrastructures, and institutions located far from the ice itself. The relevant scale is therefore no longer linked to the glacier basin alone, but the coupled cryosphere-ecosystem-society system.

Third, it may also change or refocus the questions considered scientifically relevant. While a purely glaciologically derived question might ask how much ice will be lost under a given climate scenario, questions grounded in nexus research might additionally ask how this loss affects the management of emerging ecosystems in deglaciating forelands, water regulation, aquatic and terrestrial ecosystems, hydropower production, tourist access and activities, cultural values, or hazard exposure. Questions of this nature cannot be addressed by a single discipline.

This does not imply that every glaciological study should become an ESD assessment. Rather, the ESD framework provides an opportunity to identify where disciplinary boundaries currently constrain our understanding of cryospheric change, and where multidisciplinary approaches can enrich glaciological study. Recent assessments have revealed considerable fragmentation in methods, indicators, and geographical coverage, demonstrating that a common conceptual framework is necessary but remains under development (Malinauskaite et al., 2025; Filippelli et al., 2026).

5 From multidisciplinary collaboration to nexus science

There is an important distinction between a multidisciplinary field and a multidisciplinary nexus. Multidisciplinarity can simply mean that researchers from different disciplines study the same system in parallel. A nexus approach goes further: it focuses on the relationships between processes, services, values, and decisions across disciplinary boundaries (see also Varutti et al., 2025), and moves towards something more akin to transdisciplinarity.

This distinction is particularly important for the cryosphere. Consider glacier runoff. A glaciologist can estimate future discharge, a hydrologist can model downstream availability, an ecologist can assess consequences for aquatic communities, an economist can estimate changes in hydropower or agricultural yields, and a social scientist can examine consequences for livelihoods and wellbeing. These contributions become genuinely integrative only when they are linked through a shared representation of the system - a nexus.

The ESD framework can provide such a representation for glaciology. It distinguishes between the physical or ecological process, the service and/or disservice generated by that process, the benefit or risk to people, and the values assigned to that benefit. This distinction also helps to avoid double counting and conceptual confusion, which are recognized challenges in ESD research (Haines-Young and Potschin, 2018; Filippelli et al., 2026). A mature cryosphere research nexus should also combine biophysical and ecological indicators, socio-economic information, and plural value systems, rather than reducing the cryosphere to a monetary asset.

6 Opportunities and challenges

The ESD perspective creates multiple opportunities for future cryosphere research. Adopting the nexus research approach can support integrated indicators of cryospheric change. This means that instead of communicating glacier retreat

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exclusively in terms of metres of terminus change or metres water equivalent of mass loss, future assessments could simultaneously track changes in freshwater contribution, freshly exposed substrates, ecological functions, cultural value, and hazard exposure. Recent reviews have begun to compile such indicators, but substantial methodological heterogeneity remains (Malinauskaite et al., 2025; Filippelli et al., 2026).

Nexus thinking can help to improve both adaptation and decision-making. Glacier retreat is not simply a type of environmental change; it can alter the distribution of benefits and risks among communities, sectors, and ecosystems. Identifying these trade-offs can help distinguish adaptation strategies that preserve multiple contributions from those that optimize one service at the expense of others (Zimmer et al., 2022). The ESD framework can also strengthen interdisciplinary funding capture, environmental monitoring strategies, and policy design. Observations of cryospheric processes and change are often collected independently from ecological or socioeconomic observations, but a nexus perspective encourages the development of integrated infrastructure and long-term monitoring programmes capable of detecting coupled changes across physical, ecological, and social systems.

Several challenges remain in adopting this perspective. The first is attribution: determining which portion of a service or disservice can be attributed to the cryosphere rather than to other ecosystem components or human infrastructure. The second is nonlinearity: ESD can change abruptly when thresholds in glacier, river, or ecosystem states are crossed. The third is distribution: aggregate benefits can conceal substantial inequalities between upstream and downstream populations. Finally, there is a risk that the language of ESD frames the cryosphere exclusively in instrumental terms. This can be addressed by combining ecosystem services approaches with the broader ‘Nature’s Contributions to People’ perspective, and by recognizing cultural, relational, and intrinsic values.

7 Conclusions

The integration of ESD research within cryospheric studies provides much more than just a new sub-topic under the glaciology umbrella; it is changing the conceptual boundaries of the discipline. By linking cryospheric processes to ecosystem functions, human benefits, values, and risks, ESD, twinned with nexus thinking, connects glaciology with hydrology, ecology, biogeochemistry, geomorphology, economics, social sciences, governance, and more. We propose that the emerging cryosphere research nexus should be regarded as a scientific framework rather than simply an interdisciplinary metaphor. Its defining characteristic is the explicit connection between physical cryosphere processes and the ecological and societal systems that depend on, interact with, affect, or are affected by them.

The central challenge for the next generation of cryosphere research is consequently not only to determine how rapidly glaciers, snow, permafrost, and sea ice are changing, but also to understand what these changes mean for ecosystems and societies. In this context, ESD provides a useful bridge between process-based cryospheric science and questions of human and environmental well-being. Glaciology is not becoming less physical by engaging with these questions; rather, it is becoming more consequential. The future of the discipline may therefore lie not at the boundary between glaciology and

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other fields, but in the nexus that connects them, more strongly now than ever. This approach meets the appeal of the UN-endorsed Decade of Action for Cryospheric Sciences (2025–2034) initiative, that "calls on scientists, governments, and communities worldwide to unite and protect the cryosphere and safeguard the billions of people who depend on them for their survival" (UNESCO, 2026).

As a consequence of the evolving nature of our research and multidisciplinary collaborations under climate change, the definition of a glaciologist is also changing. While it has previously focused primarily on physical geography and the physics of ice and snow; now, in the Anthropocene, a modern glaciologist can be defined as an interdisciplinary Earth systems scientist who investigates how ice interacts with climate, ecosystems, and human society, expanding far beyond the historical boundaries of measuring ice thickness or tracking glacier retreat. Consequently, this new forma mentis challenges the traditional academic siloing of funding bodies, peer-review processes, and educational curricula. If glaciers are complex socio-ecological life-support systems, the scientific community must train a new generation of "cryospheric system scientists" to meet the challenges of ongoing climate, environmental, and societal change.

Author contributions

MG led the conceptualisation of the manuscript. Both MG and CC contributed to writing.

Competing interests

One of the authors (CC) is a member of the editorial board of The Cryosphere.

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