

A scoping review of the Cryosphere's ecosystem services, disservices, and related indicators

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Abstract

The cryosphere, which refers to the parts of the Earth's surface where water is in solid form, is a major contributor to human wellbeing through the provision of vital ecosystem services. These include, e.g., groundwater recharge, water storage and purification, climate regulation, and diverse cultural and spiritual benefits. A systematized classification of ecosystem services can be used to define, measure, and value the ways in which the cryosphere contributes to society and to communicate these benefits in a clear, transparent and scientifically sound way, yet, it has been missing to date. This study builds on previous literature exploring the cryosphere's positive and negative impacts on human wellbeing in the context of rapid climate change. It further organises this knowledge on a global scale with a view to enhancing scientific exploration and policy guidance, along with facilitating comparability between different studies. Our research applies the Search-Appraisal-Synthesis-Analysis (SALSA) literature review method and the Common International Classification of Ecosystem Services (CICES) to source and systemise the existing information on ecosystem services and disservices provided by the cryosphere, and possible indicators for monitoring their changes are identified. A total of 30 ecosystem services and 10 disservices were identified, together with indicators that could be used to monitor their trends in biophysical, economic, and sociocultural terms. Our research finds that the cryosphere continues to provide vital ecosystem services despite accelerated retreat of glaciers and other cryospheric components, but also an increasing amount of ecosystem disservices because of global climate change. Monitoring trends in the cryosphere's contributions to human wellbeing has the potential to inform adaptive governance in fast-changing cryospheric environments.

Keywords: cryosphere, ecosystem services, ecosystem disservices, nature's contributions to people, ecosystem service indicators

1. Introduction

The term “cryosphere” refers to the parts of the Earth’s surface where water is in solid form (Su et al, 2019). The Intergovernmental Panel for Climate Change (IPCC, 2019, p. 4) defines it as *“the components of the Earth System at and below the land and ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost, and seasonally frozen ground”*. Its distinguishing feature is the presence of water in solid form that changes in response to environmental factors, e.g., temperature and precipitation, making the geophysical structures and functions of the cryosphere particularly vulnerable to climate change (ibid.). It is estimated that approximately 15% of the Northern Hemisphere is underlain by permafrost (Obu, 2021) and around 10% of the Earth’s surface is covered by glaciers and ice sheets (IPCC, 2019). Around four million people live in the Arctic, large parts of which lies in permafrost and ice and snow covered areas (NSIDC, 2025; Ramage et al., 2021), and the populations living in high mountain regions, where snow, permafrost and /or glaciers are prominent features of the landscape, are projected to reach between 740 and 840 million people by 2050 (IPCC, 2019; UNESCO, 2025).

The cryosphere provides essential ecosystem services (ES) to people – vital contributions to survival, health, and wellbeing, also known as nature’s contributions to people (NCP) (Díaz et al., 2018; IPBES, 2019; Pascual et al., 2023; Pascual et al., 2017). The cryosphere provides humanity with some of the most vital climate regulation services (Sturm et al., 2017); it regulates the Earth’s climatic conditions, while more than half of the world’s population depends on seasonal melting of mountain snow and ice (Milner et al., 2017; Rasul & Molden, 2019). Elements of the cryosphere areas, such as glaciers, also underpin important sacred and symbolic meanings that help people to make sense of their natural surroundings and care for their environment (Allison, 2015; Gagné, 2019). Cryosphere areas, such as the Arctic, the Antarctic, and the Himalayas, provide ES on a planetary scale, including temperature regulation, water storage, sedimentary balance, and support for global hydrological cycles (IPCC, 2019; Xiao et al., 2015). The cryosphere’s impacts also extend to ecosystem disservices (EDS) that affect human wellbeing negatively, especially as nature’s systems and functions are increasingly affected by anthropogenic impacts, such as climate change (Wu et al., 2021). These impacts often take the form of exacerbated risks to human security, e.g., through increasingly unstable permafrost, ice, and snow cover causing infrastructure damages and safety issues, increased frequency and severity of outburst floods, or the release of pathogens when glaciers retreat (Ahmed, 2024; D. Li et al., 2022; Mukherji et al., 2019; Su et al., 2019).

These ES and EDS are however changing at unprecedented rates (IPCC, 2019; Palomo, 2017). The cryosphere is among the fastest-changing environments on Earth due to climate change. Between 2000 and 2019, glaciers worldwide lost 267 gigatons of mass each year (Hugonnet et al., 2021) and glacial modelling predicts that 26-41% of their total mass will be lost by 2100 (Rounce et al., 2023), leading to sea level rise, increases in the frequency and intensity of floodings, and loss of biodiversity (Talukder et al., 2021). The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) notes that these changes have fundamental consequences for the cryosphere’s ability to provide ecosystem services, entailing *“negative impacts on food security, water resources, water quality, livelihoods, health and wellbeing, infrastructure, transportation, tourism and recreation, as well as culture of human societies, particularly for Indigenous peoples”* (IPCC, 2019, p.15). According to the same report,

cryosphere change is projected to affect water resources, e.g., agricultural irrigation in high mountain areas, livelihoods in the Arctic and hydropower potential. Moreover, the negative effects of changes in cryosphere structure and functions are likely to result in more land erosion, floods, landslides, and land destabilisation due to thawing permafrost, augmenting the risks for infrastructure, tourism, and cultural and recreational assets, which inhibits the potential to meet the United Nations' Sustainable Development Goals (UN SDGs), particularly in cryosphere and mountainous regions (Zhang et al., 2022a, 2022b).

Despite providing vital ES globally, e.g., water provision and storage and climate regulation, the cryosphere has received relatively little attention within ES scholarship, perhaps partly due to its vast scale and largely abiotic nature. There have been some efforts to list and describe the cryosphere's contributions to human wellbeing (Euskirchen et al., 2013; Mukherji et al., 2019; Su et al., 2019; Xiao et al., 2015; Zhang et al., 2022b), yet a systematic classification of ES and EDS of the cryosphere is still lacking in the literature. This gap may be a result of the challenges involved in synthesizing knowledge through the many different components that span from permafrost areas and frozen rivers and lakes to ice caps and icebergs as well as the different scales on which these (dis)benefits occur: local, regional, and global (IPCC, 2019; Qin & Ding, 2010). These different scales are important when defining ES formation, beneficiaries, valuation, and policy options (de Groot et al., 2010; Gómez-Baggethun et al., 2019; Hauck et al., 2013).

Systematic ES classifications can be used to define, measure, and accord value to the ways in which parts of the natural world contribute to society, together with informing policy and helping to communicate these benefits in a clear, transparent and scientifically sound way (Broome et al., 2024b; Finisdore et al., 2020). Alongside the Millennium Ecosystem Assessment (MEA, 2005) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019), with its focus on Nature's Contributions to People (NCPs) as equivalents to ES and EDS, the Common International Classification of Ecosystem Services (CICES) is one of the most established classifications of ecosystem benefits that is widely adopted for developing ES taxonomies across ecosystems and is well suited to account for abiotic flows, such as those present in the cryosphere (Cook et al., 2021; Haines-Young, 2023; Haines-Young & Potschin-Young, 2018). Prior to this study, a CICES classification had not been applied for ES of cryosphere as a whole, although it has been used for some of its components, e.g., glaciers (Cook et al., 2021).

This study presents the first attempt at systemising the existing knowledge on cryosphere's ES and EDS, classifying them according to CICES, and identifying possible indicators for monitoring. It systematizes available information on the cryosphere's contributions to people, with an intent to aid scholars, practitioners, and policy makers to identify the areas where their efforts could be most effective in further examining and reducing pressures on cryosphere's ES, coping with the cryosphere's EDS and adapt to their changes. The main goals of this paper are:

- 1) To identify and classify cryosphere ES and EDS using the CICES classification.
- 2) To define possible indicators for monitoring the trends in cryosphere ES and EDS change.

The paper is organised as follows. Section 2 delineates the underlying theoretical and methodological approach of the study. Section 3 presents the identified positive and negative contributions of the cryosphere to human wellbeing and a battery of indicators for monitoring their trends. Section 4 discusses the study results in the context of climate change and implications for policy and governance. Section 5 concludes with a summary of our main findings and the identification of further research avenues.

2. Theoretical background and methodological approach

2.1 Cryosphere ecosystem services

In this study, the term “cryosphere ES” is used to refer to the cryosphere’s positive contributions to human wellbeing. There are considerable differences in the literature in relation to the classification of cryosphere ES, one of the reasons being that they are primarily of abiotic origin (of geophysical nature) and that many of the benefits from the cryosphere materialise as supporting mechanisms for functions and processes that indirectly enhance human wellbeing, sometimes labelled as “supporting” or “intermediate” services (MEA, 2005; Su et al., 2019). An example of a supporting cryosphere ES could be habitat provision for species (Xiao et al., 2015; Zhang et al., 2022b) and of an intermediate ES – water supply for surrounding ecosystems that enables primary production (Mukherji et al., 2019). Cryosphere ES are susceptible to “double-counting” as different ES stem from the same or similar bio-geo-physical functions and are at a higher risk of being counted twice, e.g., water runoff regulation and flood prevention or nutrient cycling and enhancement of feed and fodder production. To avoid the double-counting of ES, the CICES classification only considers “final” ES, distinguishing them from the underlying structures, processes and functions of systems that determine their capacity to deliver ES (Haines-Young, 2023).

CICES is based on the ES cascade model that distinguishes between different stages of ES formation (Haines-Young, 2023; Potschin-Young et al., 2018; Wu et al., 2021). The ES cascade model in Figure 1, adapted from Broome et al. (2024a, p. 4), illustrates the links between the geophysical and biophysical structures, processes, and functions, human-nature co-production processes, and the resulting final ES.

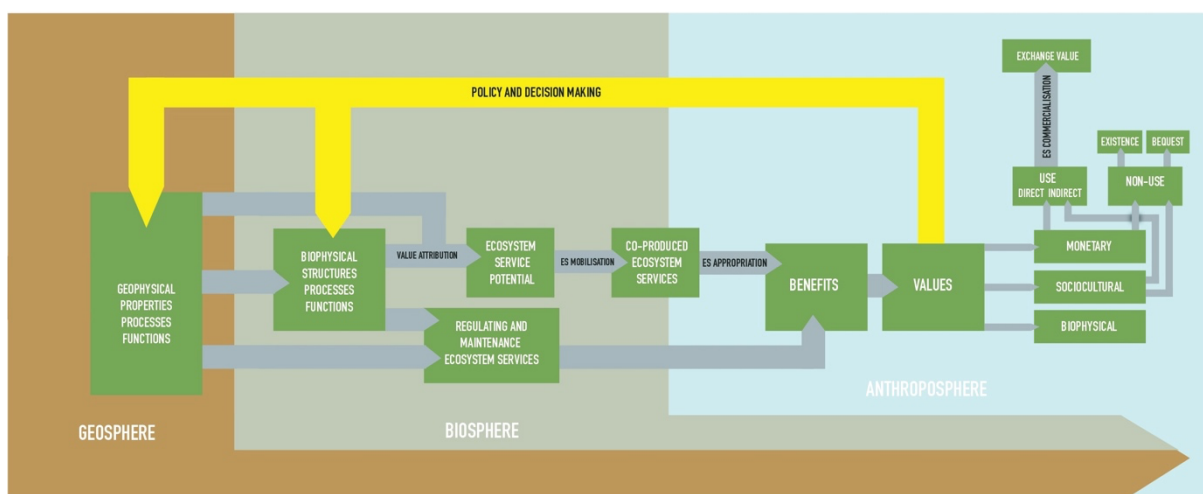


Figure 1. Cryosphere ES cascade model. Adapted with permission from Broome et al., 2024a, p. 4.

The cryosphere is a part of a geophysical structure that is closely interconnected with the biosphere, the atmosphere, the hydrosphere, land surfaces, and the anthroposphere, through which ES are formed (Marshall, 2011; Qin & Ding, 2010; Xiao et al., 2015). The cryosphere underpin ecosystem functions by supplying essential nutrients, such as nitrogen, phosphorus, potassium, calcium, and iron, the presence of which forms a foundation for primary production (Tian et al., 2019). In marine environments receiving glacial meltwater, these processes enhance the uptake of carbon dioxide by phytoplankton, thereby intensifying the efficiency of the ocean's biological pump (Wadham et al., 2019).

In the cascade model, the processes in the geosphere, biosphere and anthroposphere, together with policy and decision-making processes depicted by the yellow arrow at the top of Figure 1, constitute the main drivers of cryosphere change, determining in turn the trends in ES and EDS change. Ecosystem services materialize in the interface between ecosystem dynamics and human benefit. The beneficiaries and co-producers of cryosphere ES implied in Figure 1 include all the people who depend on these ES for survival, health, and/or wellbeing, including farmers, the energy industry, local and indigenous communities, scientists, tourists, and humanity at large.

2.2 Methodological approach

To achieve the study goals, a mixed methods approach was applied: the literature scoping review was carried out to source relevant publications on the topic, the cryosphere ES were listed and categorized following the CICES classification, their beneficiaries, scales and possible indicators for monitoring were identified, and the results then discussed in terms of their policy and governance implications in the context of climate change.

2.2.1. Identification and classification of cryosphere ecosystem services

According to (Munn et al., 2022), *“Scoping reviews are a type of evidence synthesis that aims to systematically identify and map the breadth of evidence available on a particular topic, field, concept, or issue, often irrespective of source (i.e., primary research, reviews, non-empirical evidence) within or across particular contexts.”* In this study, the aim is to identify, classify and discuss cryosphere ES, EDS and indicators. For this purpose, the Search-Appraisal-Synthesis-Analysis (SALSA) literature review methodology (Grant & Booth, 2009) was applied to identify cryosphere ES, together with their scale, beneficiaries, and possible indicators for monitoring the trends in their change. This relatively simple and reproducible literature review method has been successfully applied in a variety of ES-focussed studies to source and systematise literature, identifying the main themes, issues, and gaps (Broome et al., 2024b; Cook et al., 2021; Malinauskaite et al., 2019; Mandal et al., 2023; Merida et al., 2022).

The literature searched for this review included peer-reviewed scientific papers and high-level reports, which refers to comprehensive reports that examine the cryosphere and its contributions to people in general terms to facilitate overall understanding, rather than place-specific mechanisms behind them. The terms “cryosphere”, “ice” and “glaciers” were combined with the terms “ecosystem services” using three search queries [cryosphere AND ecosystem AND services], [ice AND ecosystem AND services], and [ice AND ecosystem AND services] in

Scopus and Web of Science academic search engines to search for studies that had these terms in the title, abstract, or keywords. The initial search produced a large number of publications: 1,717 (705 in Scopus and 1012 in Web of Science), but after the appraisal phase, 31 publications were selected for synthesis and analysis, and four additional publications were sourced through “snowball” method (pursuing references of references), resulting in 33 papers being included in the scoping review (the list of publications is provided in the Appendix A). The appraisal of publications to be included in the review was based on the three following criteria: (i) they were published no later than 2009, 15 years prior to the date of the review (2024) to ensure that information is not outdated; (ii) publications had to be peer reviewed or high-level reports listing contributions of the cryosphere to human wellbeing; and (iii) focussed on the human wellbeing impacts of the cryosphere. Following these criteria, the vast majority of publications (1,686) were excluded, leaving 31 publications, which also includes previous review studies as the main purpose was to synthesise the existing knowledge on cryosphere ES.

The identified cryosphere ES were classified according to the CICES system, which includes geophysical systems, such as ice and snow, and is based on the ES cascade model depicted in Figure 1 that differentiates different stages of ES formation. CICES version 5.2 provides guidance for a crossover to the IPBES NCP categories and the System of Environmental-Economic Accounting (SEEA) (Haines-Young, 2023). Therefore, it was deemed by the authors to be potentially most useful system in terms of universality of application. The scoping review covered studies variously including the ES/EDS and NCP concepts as they all represent ways, in which humans benefit from Earth’s natural systems (Costanza, 2024) and because share very similar theoretical tenets (Muradian & Gómez-Baggethun, 2021).

2.2.2. Definition of ecosystem service indicators and scales

Our research adopts an ES/NCP framework for assessing the capacity of nature to sustain a good quality of human life (Gómez-Baggethun et al., 2019; Helseth et al., 2022; IPBES, 2019). Following previous ES research (e.g. Baró et al. 2016) we differentiate indicators for monitoring ES changes and trends in terms of *capacity* (“ecosystem’s potential to deliver services based on biophysical properties, social conditions, and ecological functions” (Villamagna et al., 2013, p. 116), *demand* (“the amount of a service required or desired by society” (ibid.)), and *flow* (“the service actually received by people”, as per Villamagna et al. (2013, p. 118). Examples of indicators were sourced from the publications in the Appendix A, the literature on cryospheric change and indicators for its monitoring that was identified using the search query [cryosphere AND change AND indicators] in the Scopus and Web of Science databases (Box et al., 2019; Bring et al., 2016; Hobbie et al., 2017; Treat et al., 2018), or otherwise selected by the authors as proxies for assessing a specific ES, e.g., education, for which no indicators were available in the literature. Following the literature in integrated assessment and valuation of ecosystem services (Gómez-Baggethun et al., 2016) we defined biophysical, economic, and sociocultural indicators. Biophysical indicators considered are used for recording changes in physical flows and structures of cryosphere ES and EDS; economic indicators were selected to assess damages and demand; and socio-cultural and qualitative indicators were applied for assessing cultural ES.

We classified cryosphere ES and EDS as operating at three geographical/societal scales: local, regional and global (Gómez-Baggethun et al., 2019). Local scale includes the (dis)benefits on the local social-ecological system scale, often defined by a community dependent on the local ecosystem, such as a valley, section of a river, etc.; regional scale implies a larger social-ecological structure, e.g., an administrative region or a country deriving ES from a larger natural system, such as a mountain range, a watershed, or a permafrost area; and global scale implies ES/EDS that benefits the humanity at large regardless of location, e.g., carbon sequestration or existence value of glaciers. The definition of ES scale helps to define more geographically situated indicators and to take into consideration the actors to which benefits accrue and the institutions that are best suited for their governance (Burkhard & Maes, 2017; Maes et al., 2012).

3. Cryosphere ecosystem services, disservices, and indicators

3.1 Cryosphere ecosystem services

This study aims to provide a broad overview of the NCPs from the cryosphere that includes all the components of the Earth System that are frozen, with the underlying geophysical structure of ice (water in solid form). The following three sections list and describe the identified provisioning, regulation and maintenance, and cultural cryosphere ES, respectively. The three types of ES refer to CICES sections *“that relate to whether the contributions to human well-being support a) the provisioning of material and energy needs, b) regulation and maintenance of the environment for humans, or c) the non-material characteristics of ecosystems that affect physical and mental states of people”* (Haines-Young, 2023, p. 5). The 30 ES and 10 EDS that were identified are summarised and classified in accordance with CICES version 5.2 (Haines-Young, 2023), with a detailed CICES 5.2 classification of cryosphere ES is included in Appendix B. In Tables 1, 2 and 3, IPBES equivalent versions of the NCP classification (IPBES, 2019; Pascual et al., 2017) are listed where appropriate to facilitate comparison across ES classification systems. Additionally, short descriptions of the ES are provided, together with identified beneficiaries, the geographical scales at which ES are delivered, and the literature sources. In each section, examples of the cryosphere ES are provided to illustrate the inventory provided in the tables.

3.1.1 Provisioning ecosystem services

Table 1 lists the six provisioning ES derived from the cryosphere that support people’s material and energy needs.

Table 1. Provisioning (abiotic/geophysical) cryosphere ES (6).

Ecosystem service	CICES 5.2 code	IPBES type equivalent	Description	Beneficiaries	Geographical scale	References
Freshwater for drinking	4.1.1.1	Food and feed	Freshwater used for nutrition purposes	Individuals; communities; farmers; utility companies	Local; regional	Cook et al. (2021); Mukherji et al. (2019); Xiao et al. (2015)

Ecosystem service	CICES 5.2 code	IPBES type equivalent	Description	Beneficiaries	Geographical scale	References
Freshwater for sanitation, and irrigation	4.1.1.2	Materials and assistance	Surface and groundwater used for sanitation and irrigation	Households; communities; farmers	Local; regional	Cook et al. (2021); Mukherji et al. (2019); Xiao et al. (2015)
Snow and ice material for building and decoration	4.1.1.2	Materials and assistance	Provision of materials, e.g., for construction and decoration	Indigenous communities; artists	Local	Zhang et al. (2022b)
Cooling	4.1.1.3	Materials and assistance	Historical: cooling of dwellings, food, drinks; medicinal uses. Current: thermal difference power plants, plant seed banks.	Households; power companies; humanity as a whole	Local; global	Su et al. (2019)
Hydropower	4.1.1.3	Energy	Surface water used for energy generation	Communities; energy companies; states	Local, regional	Cook et al. (2021); Mukherji et al. (2019); Xiao et al. (2015)
Feed and fodder production enhancement	4.1.X.X	Food and feed	Support of snow cover for primary production in mountain rangelands	Farmers; communities	Local; regional	Mukherji et al. (2019); Paudel and Andersen (2010)

The cryosphere plays a crucial role in ensuring the supply of freshwater for drinking, sanitation, irrigation, and hydropower (Cook et al., 2021; Mukherji et al., 2019; Xiao et al., 2015) as well as snow and ice material for cooling, building, and decoration (Su et al., 2019; Zhang et al., 2022a). For instance, glaciers play a vital role in supplying valuable freshwater to the inhabitants of high mountainous and polar regions, ensuring the sustenance of local populations, industry, and agriculture (Xiao et al., 2015). Mountain communities rely on the cryosphere for their drinking, cooking, irrigation, and other domestic water needs (Mukherji et al., 2019).

The Himalayan glaciers are a major water source for the most populous region of the planet, including India and China – supported by the Ganges, Yellow and Yangtze rivers, also known collectively as the Asian Water Towers (Cook et al., 2021; Immerzeel et al., 2020). Meltwater from glaciers and snow fulfils the water demands of nearly 800 million people in the high mountains of Asia (Pritchard, 2019; Rasul & Molden, 2019), with 129 million farmers depending upon the seasonal release of glacial meltwater (Biemans et al., 2019; ICIMOD, 2023). There has also been a notable proliferation of commercially accessible, premium-grade glacier water sources worldwide, with a variety of mineral water brands (Xiao et al., 2015).

Cryosphere and glacial runoff contribute substantially to hydropower production, especially in countries where hydropower is the primary source of electricity (76 % in Iceland; 88% in Norway; 54-67% in Austria; and 58% in Switzerland) (Milner et al., 2017). Cooling energy from the cryosphere has been used since ancient times: ice blocks were gathered during the winter season and stored for various purposes in the summer for, e.g., cooling and preserving food, preserving deceased bodies, and treating medical conditions Su et al. (2019). Zhang et al. (2022a) highlights the uses of ice and snow for building and decoration, e.g., for igloos, snow caves, and ice sculptures.

3.1.2 Regulation and maintenance ecosystem services

Table 2 lists the 15 regulation and maintenance ES identified in the review that contribute to favourable environmental conditions for human life. Two of them classified as biotic because they occur in bio-geophysical processes, namely carbon sequestration and nutrient cycling through biological processes.

Table 2. Regulation and maintenance (abiotic/geophysical unless other stated) cryosphere ES (16).

Ecosystem service	CICES 5.2 code	IPBES type equivalent	Description	Beneficiaries	Geographical scale	References
Water runoff regulation	5.2.1.2	Regulation of freshwater quantity, location, and timing	Water runoff from melting snow and ice, usually controlled by temperature, often seasonal	Communities; farmers; society at large	Local; regional	Mukherji et al. (2019); Xiao et al. (2015)
Flood protection	5.2.1.2	Regulation of hazards and extreme events	Timely discharge of meltwater shielding downstream communities from glacial outburst floods	Communities downstream from glaciers	Local; regional	Cook et al. (2021); Huggel et al. (2020)
Drought prevention	5.2.1.2	Regulation of freshwater quantity, location, and timing	Meltwater sustaining streamflow and acting as a buffer during periods of drought	Communities; farmers	Local; regional	Pritchard (2019); ICIMOD (2023)
Water storage	5.2.1.2	Regulation of freshwater quantity, location and timing	Water storage in glacial lakes and reservoirs	Communities near glacial lakes; societies at large	Local; regional	Cook et al. (2021); Shugar et al. (2020)
Water purification	5.1.1.3	Regulation of freshwater and coastal water quality	Trapping water impurities through crystallisation of water and snow into ice	Users of glacial water: communities; consumers buying bottled water	Local; regional; global	Cook et al. (2021)
Carbon sequestration (abiotic)	5.1.1.3	Regulation of climate	Sequestration of GHG in permafrost and ice	Societies at large	Global	Euskirchen et al. (2013); Anisimov et al. (2017)
Carbon sequestration (biotic/ biophysical)	2.3.6.1	Regulation of climate	Biogeochemical/ physical weathering of microbial communities in ice sheets resulting in organic carbon storage	Societies at large	Global	Cook et al. (2021); Wadham et al. (2019); Peter and Sommaruga (2016); Hood et al. (2015)
Cycling of organic carbon (biotic/ biophysical)	2.4.X.X	Regulation of climate	Biogeochemical/ physical weathering of microbial communities in ice sheets resulting in cycling of organic carbon	Societies at large; users of ocean resources	Global	Wadham et al. (2019); Tian et al. (2019); Rasul and Molden (2019); Milner et al. (2017)

Ecosystem service	CICES 5.2 code	IPBES type equivalent	Description	Beneficiaries	Geographical scale	References
Increased ocean primary productivity through supply of minerals	5.2.2.1	Regulation of ocean acidification	Direct nutrient fertilisation of marine ecosystems by minerals available in glacial meltwater	Societies at large; users of ocean resources	Regional; global	Wadham et al. (2019); Tian et al. (2019); Peter and Sommaruga (2016)
Climate regulation	5.2.2.2	Regulation of climate	Albedo effect of ice that reflects sunlight, reducing surface temperatures	Societies at large	Global	Cook et al. (2021); Milner et al. (2017); Musacchio et al. (2019)
Water temperature regulation	5.2.2.1	Regulation of freshwater and coastal water quality	Glaciers and sea ice help to keep stable temperature in water bodies and oceans	Users of water resources; society at large	Local; regional; global	Cook et al. (2021); Lencioni et al. (2015)
Groundwater formation and recharge	5.2.1.2	Regulation of freshwater quantity, location, and timing	Groundwater formation and recharge through meltwaters derived from glaciers and snowpacks	Communities	Local	Lone et al. (2021); Mukherji et al. (2019)
Load bearing and support provided by ice, frozen ground, and permafrost	5.3.X.X	Reduction of hazards and extreme events	Load bearing capacity of solid ice and permafrost that support infrastructure and enable many activities, such as ice hunting	Communities; societies in locations with permafrost and ice sheets; indigenous hunters and fishermen	Local; regional	Mukherji et al. (2019); Su et al. (2019)
Erosion, rockfall and landslide protection	5.2.1.1	Reduction of hazards and extreme events	Suppression of terrestrial erosion due to solidity of frozen earth, ice and snow cover	Communities in high mountain and frozen areas; visitors	Local	Mukherji et al. (2019); Su et al. (2019)
Environmental pollution regulation	5.1.1.4	Reduction of hazards and extreme events	Retention of contaminants and facilitation of biogeochemical processes related to organic, inorganic, and particulate substances	Communities; societies at large	Local; global	Zhang et al. (2022b); Milner et al. (2017); Rasul and Molden (2019); X. Wang et al. (2020)
Habitat for endemic species	5.3.X.X	Habitat creation and maintenance	Glaciers and permafrost areas host a variety of cold adapted taxa, from bacteria to vertebrates	Users of endemic species, e.g., Arctic indigenous communities; society at large	Local; global	Lencioni et al. (2015); Vincent et al. (2011); Gobbi et al. (2021)

Many agricultural practices rely on a continuous water supply from the cryosphere (Gagné et al., 2014). Glacial meltwater is a major water source for irrigation and soil moisture in high mountain regions including the Himalayas, the Andes, and the Alps, as well as the Tien Shan and Pamir mountains of Central Asia (ICIMOD, 2023; Rasul & Molden, 2019). For instance,

owing to extreme aridity in Ladakh, India, cultivation is not possible without the use of glacial meltwater (Clouse, 2016; Mukherji et al., 2019; Norphel & Tashi, 2015). The agricultural sector in Alberta relies heavily on meltwater sourced from nearby glaciers in the Canadian Rockies (Milner et al., 2017).

The cryosphere regulates water runoff in terms of quantity, location, and timing (Xiao et al., 2015). Glacier meltwater plays a vital role in sustaining streamflow and can act as a critical buffer during periods of drought (ICIMOD, 2023; Mukherji et al., 2019). Through the phenomenon known as "peak shaving and valley filling", glaciers accumulate significant quantities of frozen water during cold or humid seasons, which they subsequently release during hot or drought periods, and this process contributes to the relative stability of river runoff on seasonal timeframes, enabling effective utilisation and management of regional water resources, particularly in arid regions and during drought conditions (Su et al., 2019; Xiao et al., 2015). Pritchard (2019) estimates that glacier meltwater provides for the basic needs of 221 ± 59 million people and are particularly crucial during summer drought events, and the same is true for many Arctic communities (IPCC, 2019).

Seasonal cryosphere changes enable the timely discharge of meltwater, shielding downstream communities from glacial outburst floods (Huggel et al., 2020). In high mountain regions, glacial meltwater plays a substantial role in recharging groundwater reserves; for instance, in the Upper Indus River Basin, meltwater contributes up to 83% of the annual groundwater recharge (Lone et al., 2021). The cryosphere also provides water storage in the form of frozen water, glacier lakes, and reservoirs (Shugar et al., 2020). Biogeochemical processes involving the cryosphere, where organic, inorganic, and particulate contaminants are removed from the environment and stored in ice, e.g., persistent organic pollutants (POPs), help to regulate environmental pollution (Rasul & Molden, 2019; X. Wang et al., 2020).

The cryosphere's role in the global carbon cycle operates through the accumulation of organic carbon from in-situ primary production, the deposition of carbonaceous materials derived from terrestrial and anthropogenic sources (Hood et al., 2015), the greenhouse gas (GHG) emissions resulting from the microbial respiration of organic matter (OM) stored within glaciers, and the enrichment of downstream ecosystems facilitated by the release of nutrient-rich glacial meltwaters (Wadham et al., 2019). Hood et al. (2015) estimate that nearly twice as much Particulate Organic Carbon (POC) relative to Dissolved Organic Carbon (DOC) is released by glacial runoff to downstream ecosystems. Hence, glacier surfaces possess the capacity to serve as both sources and reservoirs for carbon-containing aerosols (Peter & Sommaruga, 2016). Upon release, DOC can fuel carbon cycling in riverine systems and support the sustenance of aquatic food webs in glacier-fed rivers (Milner et al., 2017). Moreover, glacial crushing and grinding generates highly pulverized rock particles which act as a source for electron donors, such as organic matter, hydrogen, and micro-macro nutrients (Wadham et al., 2019).

The cryosphere plays a significant role in modulating both global and regional climate due to their high albedo, i.e., they reflect the incoming shortwave radiation back to the atmosphere (Xiao et al., 2015). In addition to global climate regulation, glaciers and ice sheets have a local cooling effect (Mukherji et al., 2019). The cryosphere helps to regulate water temperatures through the release of cold-water flows, which is important for some temperature-sensitive aquatic species, e.g., aquatic insects and some species of fish, such as trout and salmon (Cook

et al., 2021). Glaciers and permafrost-related landforms provide habitats to a variety of cold-adapted taxa from bacteria to vertebrates, which have been included in the Natura 2000 network in Europe (Gobbi et al., 2021; Vincent et al., 2011).

Cryosphere has historically been vital for accessibility, mobility, transportation, and infrastructure in permafrost and high mountain regions due to its solidity which enables passage in cold regions, e.g., early human migration across continents, trade routes, and providing physical support for infrastructure (Su et al., 2019). Due to its solidity and binding qualities, cryosphere elements reduce land erosion, landslides, and rockfalls in the mountainous areas (Mukherji et al., 2019; Su et al., 2019).

3.1.3 Cultural ecosystem services

Table 3 lists the 8 cultural cryosphere ES that affect physical and mental states of people in non-material ways.

Table 3. Cultural (abiotic/geophysical) cryosphere ES (8).

Ecosystem service	CICES 5.2 code	IPBES type equivalent	Description	Beneficiaries	Geographical scale	References
Recreation and tourism	6.1.1.1	Physical and psychological experiences	Features of the cryosphere, e.g., glacier and snow, create conditions for recreational activities	Visitors; communities	Local; regional	Cook et al. (2021); Su et al. (2019)
Enhancement of scientific and traditional knowledge	6.2.1.1	Learning and inspiration	Cryosphere environments facilitate research and observation that enhances knowledge about them	Research community; indigenous knowledge holders; society at large	Local; regional; global	Su et al. (2019)
Education	6.2.1.2	Learning and inspiration	Elements of the environments that facilitate in-situ or remote learning	Educational institutions; educators; learners; society at large	Local; regional; global	Cook et al. (2021)
Aesthetics	6.2.1.4	Physical and psychological experiences	Aesthetic enjoyment of features of the cryosphere	Societies at large; communities; visitors	Local; global	Cook et al. (2021); Schirpke et al. (2016)
Artistic inspiration	6.3.1.1	Learning and inspiration	Inspiration for creating works of art	Artists; consumers of art; societies at large	Local; global	Cook et al. (2021); Xiao et al. (2015)
Spiritual enrichment	6.4.1.2	Physical and psychological experiences	Spiritual experiences facilitated by cryosphere areas and elements	Communities; religious groups	Local; regional	Cook et al. (2021); Gagné (2019); Mukherji et al. (2019); Milner et al. (2017)
Community identity	6.4.1.1	Supporting identities	Sense of community identity supported by presence of cryosphere	Communities	Local	Cook et al. (2021)
Existence and bequest values	6.4.2.2	Maintenance of options	Perception of intrinsic value of the cryosphere and importance of preserving it	Communities; societies at large; future generations	Global	Cook et al. (2021); Kronenberg (2013)

The cryosphere supports cultural identities, nature-based experiences, and diverse aesthetic, symbolic, and spiritual values both directly and indirectly. It also contributes to national economies, with tourism activities ranging from sightseeing and glacier walks to ice climbing, skiing, and trekking (Gagné et al., 2014; Milner et al., 2017). Glacier tourism serves as a significant economic catalyst in numerous regions, attracting approximately 30,000 visitors annually in Norway, while the glaciers of Banff National Park in Canada draw over three million visitors, and Austria's Pasterze Glacier attracted around 800,000 visitors annually (Milner et al., 2017). In New Zealand, glacier tourism is estimated to contribute approximately USD \$84 million to the economy on an annual basis (ibid.).

The cryosphere supports enhancement of scientific and traditional knowledge through research, observations, and experiential knowledge specific to snow and ice rich environments, e.g., building igloos and ice hunting/fishing (Su et al., 2019). It also helps to provide opportunities for formal and informal education, e.g., through visitor centres and in situ experiences (Cook et al., 2021). Another type of experience valued by cryosphere enthusiasts is the aesthetic aspect, as has been demonstrated in a photo-based survey in the Alps, where the highest aesthetic values were attributed to high altitude vistas, including glaciers and snow-caps (Schirpke et al., 2016). Cryosphere elements, such as glaciers and snow-covered mountains, possess a distinctive allure that inspires artistic expressions through literature, film, photography, logos, sculpture, architecture, and various other forms of human creativity (Xiao et al., 2015).

Glaciers hold major cultural and spiritual significance as they are considered sacred dwellings of deities and spirits that safeguard local socio-ecological systems (Allison, 2015). In India, many pilgrims embark on a journey across the Gangotri Glacier, considering it a sacred site (Milner et al., 2017). Similarly, in Canada's Yukon Territory, indigenous communities regard glaciers as divine entities with the capacity to perceive human actions (Xiao et al., 2015). In Ladakh, the elderly perceive glaciers and their lakes to be sacred havens (Mukherji et al., 2019). Glaciers and mountains are intimately tied to the identities of monks and highlanders in the Himalayas, providing them with a sense of community and identity (ICIMOD, 2023). The non-use and bequest values of the cryosphere provide a strong motivation for indigenous communities and society at large in their efforts to protect the cryosphere for its own sake (Cook et al., 2021; Kronenberg, 2013; Ruiz-Pereira et al., 2023).

3.2 Ecosystem disservices of the cryosphere

In addition to the positive contributions of the cryosphere to human wellbeing listed above, the specialized literature is increasingly extending the risks associated with change and the negative impacts to human wellbeing (IPCC, 2019; Mukherji et al., 2019; Su et al., 2019). Including EDS allows for a more comprehensive and balanced view of human-nature dynamics (Gómez-Baggethun & Barton, 2013; Lyytimäki & Sipilä, 2009; Wu et al., 2021). Wu et al. (2021) follows the CICES classification for EDS: provisioning EDS refer to the material products that are lost; regulating EDS – to the harm caused by (de)regulation of eco/geosystem processes and functions; and cultural EDS – to non-material harm deriving from ecosystems (Broome et

al., 2024b; Lyytimäki & Sipilä, 2009; Wu et al., 2021). Table 4 lists the EDS identified in the literature review (only regulation and maintenance EDS of the cryosphere were identified).

Table 4. Cryosphere EDS, all of which fall under the CICES regulation and maintenance section.

Ecosystem disservice	IPBES type equivalent	Description	Groups affected	Geographical scale	References
Flooding	Regulation of hazards and extreme events	River floods due to melting ice; glacier lake outburst floods	Communities living downstream from glaciers	Local; regional	Mukherji et al. (2019); Pertierra et al. (2021)
Avalanches	Regulation of hazards and extreme events	Avalanches causing damage to health, property, and infrastructure	Communities and visitors in areas with avalanche risk	Local	Mukherji et al. (2019)
Constraining habitat for fauna and flora	Habitat creation and maintenance	Cryosphere as a hostile environment for biota	Society at large; local communities	Local; regional	Mukherji et al. (2019)
Glacier sedimentation	Formation, protection and decontamination of soils and sediments	Sediment generation and export from glaciers to rivers and oceans	Society at large; local communities; hydropower producers	Local; regional	Herman et al. (2021); D. Li et al. (2022)
Risks associated with winter sports	Physical and psychological experiences	Risks of injuries or fatalities, e.g., by avalanches, ice crevices, storms, low temperatures	Winter sports participants; medical staff	Local	Su et al. (2019)
Sea level rise	Regulation of hazards and extreme events	Melting ice sheets increase global sea level	Coastal cities and communities; societies at large	Global	Pertierra et al. (2021)
Pollution from melting	Regulation of hazards and extreme events	Melting ice as a local secondary source of POPs	Communities living downstream from melting glaciers/ice	Local; regional	Peter and Sommaruga (2016); J. Li et al. (2017)
Increased surface erosion and instability	Regulation of hazards and extreme events	Cryosphere changes resulting in decreased surface stability	Communities	Local; regional	Mukherji et al. (2019); Su et al. (2019)
Climate deregulation by released carbon sources to atmosphere	Regulation of climate	Increased GHG emissions due to thawing permafrost	Society at large	Global	Mukherji et al. (2019); Euskirchen et al. (2013)
Climate deregulation by reduced albedo effect	Regulation of climate	Reduced reflection of sun rays due to reduction in ice and snow surface	Society at large	Global	Euskirchen et al. (2013)

The first five cryosphere EDS listed in Table 4 affect human wellbeing negatively through the outcomes of their functions and geophysical structures. The other five EDS occur due to or are amplified by the warming climate that induces changes in the structural and functional patterns of the cryosphere elements on the supply side of the ES cascade model (Fig. 1). These EDS include the last five ES in Table 4: sea level rise, pollution, increased surface erosion and instability, and climate de-regulation EDS related to increased GHG emissions due to thawing permafrost and reduced albedo effect. Flooding EDS can be seasonal or/and climate change

induced. Other EDS, such as the risks associated with slippery surfaces, winter sports, snow avalanches, and snowstorms, are also affected by climate change, albeit to a lesser degree.

3.3 Indicators for cryosphere ecosystem services and examples of trends

Indicators can be defined as “reference tools that can be used to regularly update [the] status, rates of change, or trends of a phenomenon” (Kenney et al., 2016, p. 86). The indicators identified here measure ES capacity (potential to deliver ES), flow (actual use of ES), and demand (human need for ES) (Baró et al., 2016; Villamagna et al., 2013). Applied to appropriate geographical scales, the indicators could reveal trends in cryosphere ES and EDS availability, demand and use, which may be used for monitoring and to inform decision-making. Table 3 lists the selected indicators, together with the ES/EDS they have a potential to measure. Some of the indicators found in the literature only apply to one part of the cryosphere, e.g., sea ice, the Arctic, or permafrost areas with adjacent vegetation, yet most of them are cryosphere-specific and can be applied in different cryosphere environments. For instance, while a linear relationship between ES delivery and the size of the underlying physical structures cannot be assumed, changes in annual glacier mass balance (measured by ice volume in km³) (Box et al., 2018) can potentially be used as a proxy indicator for estimating trends in some ES provided by glaciers, assuming that larger mass/volume indicates greater ability to provide ES and vice versa, and that the opposite is true for EDS, e.g., glacier outburst floods and sedimentation increase as glaciers melt.

Table 5. Identified indicators for assessing changes in the provision of cryosphere ES and EDS.

Indicator and measurement units	Measurement units	ES/EDS measured	Capacity/flow/demand	Value domain
Provisioning ES indicators				
Freshwater use	m ³ /capita	Freshwater for drinking; freshwater for sanitation, and irrigation	Demand	Biophysical
Sales of glacial water	EUR; USD	Freshwater for drinking	Demand	Economic
Volume of water reservoirs	m ³	Freshwater for drinking; freshwater for sanitation, and irrigation	Flow/capacity	Biophysical
Price of freshwater unit	EUR/m ³	Freshwater for drinking; freshwater for sanitation, and irrigation	Demand	Economic
Number of ice buildings, artefacts; volume of ice used	number; m ³	Snow and ice material for building and decoration	Flow	Biophysical
Energy equivalent of cooling services	kWh	Snow and ice material for cooling (“cold energy”)	Flow	Biophysical
Energy generated	kWh	Hydropower	Flow	Biophysical
Market price of energy	EUR; USD	Hydropower	Demand	Economic
Spring snow cover duration in rangelands	Number of days	Feed and fodder production enhancement	Capacity	Biophysical
peak greenness in rangelands	NDVI	Feed and fodder production enhancement	Capacity	Biophysical
Number of animals kept in rangeland areas	number	Feed and fodder production enhancement	Flow/demand	Biophysical
Regulation & maintenance ES indicators				

Glacier mass balance change	$\Delta m^3/\text{time period}$	Most ES dependent on glaciers	Capacity/flow	Biophysical
Changes in volume of seasonal water runoff	$\Delta m^3/\text{time period}$	Water runoff regulation	Capacity	Biophysical
Changes cryosphere-fed river discharge	$\Delta km^3/\text{yr}$	Water runoff regulation	Flow	Biophysical
Avoided damage costs from flooding or drought	EUR; USD	Flood protection; drought prevention	Demand	Economic
Volume of water stored in glacial lakes and reservoirs	m^3	Water storage	Capacity	Biophysical
Volume of ice- and glacier- filtered water consumed	m^3	Water purification	Capacity	Biophysical
People dependent on ice- filtered water	number	Water purification	Demand	Biophysical
Long-term atmospheric CO ₂ measurements in cryosphere areas	parts per million (ppm)	Carbon sequestration; cycling of organic carbon	Flow	Biophysical
Changes in phytoplankton primary production in waters adjacent to cryosphere	$\Delta g C m^{-2} yr^{-1}$	Cycling of organic carbon; increased primary productivity through mineral supply	Flow	Biophysical
Changes in bioavailable phosphorus input to cryosphere- adjacent waters	$\Delta P Gt yr^{-1}$	Increased ocean primary productivity through mineral supply	Flow	Biophysical
Air temperature change	$\Delta ^\circ C/yr$	Climate regulation	Flow	Biophysical
Changes in precipitation	$\Delta mm/yr$	Climate regulation	Flow	Biophysical
Water temperature change	$\Delta ^\circ C/yr$	Water temperature regulation	Flow	Biophysical
Volume/fluctuations of groundwater in reservoirs	Δm^3	Groundwater formation and recharge	Capacity	Biophysical
Average temperatures in the upper 10–20 m of the ground in permafrost areas	$^\circ C$	Load bearing and support provided by ice, frozen ground, and permafrost	Capacity	Biophysical
Active layer thickness	m	Load bearing and support provided by ice, frozen ground, and permafrost	Capacity	Biophysical
Permafrost extent for the Northern Hemisphere (north of 30°)	km^2	Load bearing and support provided by ice, frozen ground, and permafrost	Capacity	Biophysical
Cost of infrastructure damages due to thawing permafrost	EUR; USD	Load bearing and support provided by ice, frozen ground, and permafrost	Demand	Economic
Replacement cost of natural barriers to erosion	EUR; USD	Erosion, rockfall and landslide protection	Demand	Economic
Water acidity change in waters adjacent to glaciers and ice sheets	ΔpH	Environmental pollution regulation; carbon sequestration	Flow	Biophysical
Presence/change in concentration of POPs	$\mu g/L; \mu g/kg$	Environmental pollution regulation	Flow	Biophysical
Endemic species' population changes	$\Delta \text{number/density}$	Habitat for endemic species	Flow	Biophysical
Temporal and spatial variability of sea ice extent and thickness	$km^2; m$	Habitat for endemic species	Capacity	Biophysical
Cultural ES indicators				

Number of visitors to cryosphere areas	number	Recreation and tourism	Flow/demand	Sociocultural
Income generated from tourism	amount	Recreation and tourism	Flow/demand	Economic
Number of publications on elements of cryosphere	number	Enhancement of scientific and traditional knowledge	Flow	Sociocultural
Traditional knowledge records	number	Enhancement of scientific and traditional knowledge	Flow	Sociocultural
Funding for cryosphere research and education	EUR; USD	Enhancement of scientific and traditional knowledge; education	Flow	Economic
Educational activities	number	Education	Flow	Sociocultural
Number of cryosphere researchers		Education	Flow	Sociocultural
Narratives and art expressing aesthetic experiences	qualitative	Aesthetics	Flow	Sociocultural
Artwork created/sold	number; EUR; USD	Artistic inspiration	Flow/demand	Sociocultural/economic
Narratives of spiritual experiences	qualitative	Spiritual enrichment	Flow	Sociocultural
Number of pilgrimages	number	Spiritual enrichment	Flow/demand	Sociocultural
Narratives of community identity	qualitative	Community identity	Flow/demand	Sociocultural
Willingness to pay to preserve cryosphere areas	EUR; USD	Existence and bequest values	Demand	Economic
EDS indicators				
Damage costs from flooding	EUR; USD	Flooding; sea level rise	Flow	Economic
Change in insurance premiums	EUR; USD	Flooding; sea level rise	Flow	Economic
Change sea level rise	Δ m	Sea level rise	Flow	Biophysical
Changes in ocean water salinity	Δ ppt; g/L	Sea level rise	Flow	Biophysical
Presence/concentration of POPs	$\mu\text{g/L}$; $\mu\text{g/kg}$	Environmental pollution	Flow	Biophysical
Damage costs of avalanches	EUR; USD	Avalanches	Flow	Economic
Damage costs of snowstorms	EUR; USD	Snowstorms	Flow	Economic
Cost of erosion events, e.g. landslides	EUR; USD	Increased surface erosion and instability	Flow	Economic
Non-growing season methane emissions from permafrost areas	Mg/yr	Climate deregulation by released carbon sources to atmosphere	Flow	Biophysical
Long-term atmospheric CO ₂ measurements in cryosphere areas	ppm	Climate deregulation by released carbon sources to atmosphere	Flow	Biophysical
Albedo anomalies	%	Climate deregulation by reduced albedo effect	Flow	Biophysical
Changes in sedimentation	Δ m ³ /m ² ; Δ kg/m ²	Glacier sedimentation	Flow	Biophysical
Changes in insurance premiums for winter sports	Δ EUR; USD	Risks associated with winter sports	Demand	Economic

Annual average temperatures in the upper 10–20 m of the ground in permafrost areas, changes in the thickness of the active earth layer, and permafrost extent in the Northern hemisphere are indicators of the state of permafrost and the ES derived from it (Box et al., 2019; Hobbie et al., 2017; Smith et al., 2022; Westermann et al., 2024). Changes in

precipitation have been used as indicators of climate regulation effects of the cryosphere in the Arctic (Bliss et al., 2017; Box et al., 2019). The normalised difference vegetation index (NDVI) satellite measure of peak greenness at annual or seasonal periods can be used to measure enhancement of vegetation (Box et al., 2019) and spring snow cover duration (measured in days) (Box et al., 2019; Brown et al., 2017) can both serve as proxy indicators for the enhancement of feed and fodder production ES. Variations in bioavailable phosphorus input of cryosphere-adjacent oceans and seas (Hawkings et al., 2016) can be used as a proxy indicator for enhanced primary productivity through the supply of minerals.

Long-term atmospheric CO₂ measurements in cryosphere areas (e.g., Barrow, Alaska) can reveal trends in regional land-surface CO₂ anomalies and indicate long-term changes in seasonal carbon uptake and respiration, signalling changes in the carbon cycle that relate to climate regulation and carbon sequestration ES and the release of EDS (Jeong et al., 2018; Ramage et al., 2024; Virkkala et al., 2025). Records of albedo anomalies – changes in the amount of sun energy reflected back to space (%) can be used as an indicator for cryosphere change-induced reductions in the albedo effect (NASA Earth Observatory, 2014). Non-growing season methane emissions in permafrost areas capture some of the climate deregulation through GHG emissions from permafrost (Treat et al., 2018). Changes in cryosphere-fed river discharge can be used to approximate trends in water runoff regulation ES and flooding EDS (Box et al., 2019), while changes in sedimentation (delivery of organic matter and nutrients) in near-coastal cryosphere zones – glacial sedimentation EDS (Bring et al., 2016). The presence and concentration of POPs (Rasul & Molden, 2019) is an indicator of environmental pollution regulation.

Rates and magnitudes of change in extent, area, thickness, spatial distribution, and most aspects of the temporal and spatial variability of sea ice indicate changes in cold water habitats and water temperature regulation ES (Box et al., 2019). Phytoplankton production, water pH and salinity in cryosphere areas can also be used as indicators for these ES (Meier et al., 2014; Vihma et al., 2016). Changes in populations of species dependent on the cryosphere, e.g., sea birds and marine mammals (Meier et al., 2014) along with plant and animal abundance with point frame and species counts (Hobbie et al., 2017) can be used as proxies for habitats in respect of endemic species.

4. Discussion

4.1 Cryosphere's ecosystem services and disservices in the warming climate

The cryosphere is a geophysical structure that depends on environmental conditions allowing the presence of ice, which is largely determined by the climate. For this reason, climate change is currently the main driver of changes in cryosphere ES and EDS (IPCC, 2019; Vincent et al., 2011). Palomo (2017) classifies the impacts of climate change on the cryosphere in the high mountain areas into impacts on food and feed production, water availability, natural hazards regulation, spirituality and cultural identity, aesthetics, and recreation. These impacts occur through geo-bio-physical changes in cryosphere areas that affect the availability of ES, creating direct impacts upon the livelihoods and culture of the people living in those areas.

With the growing Earth's population, the demand for cryosphere ES is likely to further increase, while its ability to supply them is likely to further decrease as climate change intensifies (IPCC, 2019; Rasul & Molden, 2019). Chen et al. (2016) found decreasing water storage capacity in the Tianshan Mountains in Central Asia from 2003–2013, with a decline rate of -3.72 mm/a , which suggests water tower storage capacity loss in the region of around $-2.23 \times 10^8 \text{ m}^3/\text{a}$ over this period, while the runoff has increased significantly since 1960. At the same time, much of the world's future population growth is projected to occur in the areas adjacent to the Asian Water Towers, placing even greater strain on the water resources (Immerzeel et al., 2020).

Accelerated melting of glaciers and degradation of permafrost have led to the proliferation of high-altitude lakes in the Tibetan Plateau, resulting in the loss of grazing areas for livestock (ICIMOD, 2023; Nyima & Hopping, 2019). In the upper reaches of the Querococha watershed in Peru's Cordillera Blanca, the declining spring flows resulting from the retreat of Andean glaciers have adversely impacted pasture health and grass productivity (Vuille et al., 2018). Furthermore, the reduction in water availability for livestock during the dry season has had detrimental effects on agricultural livestock productivity (Rasul & Molden, 2019; Vuille et al., 2018).

Depletion of the cryosphere, including glaciers in the mountainous regions, disrupts their visual characteristics and impacts the cultural and belief systems of the Indigenous populations, and has the potential to reduce the influx of visitors, leading to reduced employment opportunities and decreased revenues for the local communities involved in the tourism sector (ICIMOD, 2023; S.-J. Wang & Zhou, 2019). For instance, the Mittelbergferner Glacier in the Austrian Alps has experienced a substantial retreat since the early 20th century, resulting in a net loss of more than 50% of its area, with huge detrimental effects on the skiing industry in the region (Gagné et al., 2014). In China, the disappearance of glaciers on the Yulong snow mountain led to an estimated 40% decline in domestic tourism, resulting in economic losses worth 104-228 million USD per annum (Mukherji et al., 2019).

Even if mitigation efforts were to succeed in limiting global temperature increases to 1.5°C as sought by the Paris Agreement, which is becoming increasingly less likely given the current Intended Nationally Determined Contributions (INDCs) by nation states (UNEP, 2024), Asia's glaciers are likely to decrease to 64-67% of their current mass by the end of the century (Kraaijenbrink et al., 2017). Crossing this threshold threatens to alter the cryosphere regions in unprecedented and unpredictable ways, and governance efforts should be focused first and foremost on decisive action against climatic change as delayed action results in escalating risks and costs, and reduced capacity of the cryosphere to provide essential ES (IPCC, 2019).

4.2 Implications for adaptation

While there is an urgent need to drastically reduce GHG emissions and mitigate climate change to halt the detrimental impacts on the cryosphere, adaptation measures are already necessary to address the negative impacts of cryosphere ES/EDS change on human wellbeing and capture the positive ones (Qin & Ding, 2010; Rasul et al., 2020). As understanding of their importance to the Earth's functioning and human wellbeing has improved, there have been

increasing efforts to apply adaptive management strategies to the polar and mountainous regions (Hovelsrud et al., 2011; Ibsen, 2018).

Due to similarities between the governance challenges faced by the two polar regions and the Himalayan Third Pole, Ibsen (2018) suggests that inter-regional cooperation and learning is critical. Adding the ES/EDS concept into this discussion presents a potential means of translating the changes in the cryosphere into human wellbeing effects and better informing policymaking (Hauck et al., 2013; Malinauskaite et al., 2019).

Barandun et al. (2020) suggest that observational databases for monitoring and well-calibrated models in connection with climate scenarios are necessary to adapt to cryosphere change and reduce the vulnerabilities of local populations. Assessing how the provisioning of NCPs is impacted, along with what is needed to buffer such effects on societies within different geographical areas and time scales has the potential to provide guidance for climate adaptation. This illustrates the importance of defining suitable ES and EDS indicators. For instance, increasing “last chance tourism” provides enjoyment to visitors and economic opportunities to locals, but it often exacerbates environmental problems and puts pressure on local infrastructure, requiring adaptive planning to increase benefits from tourism and recreation (Lemelin et al., 2011). Similarly, short-term hydro energy supply maximisation requires additional investments in infrastructure, but it can create problems in the long-term when the supply decreases (Cook et al., 2021). In terms of EDS, as glacier outburst floods become more frequent, communities are by necessity forced to install essential physical adaptive measures, such as spillways and diversion canals, as well as planning measures, such as community-based land-use strategies, and Early Warning Systems (EWS) (Ahmed, 2024). . In response to glacier retreat and subsequent decline in water flows, local communities have pioneered the construction of artificial glaciers as ice storage devices to secure water provision in critical times of the growing season (Clouse, 2016; Norphel & Tashi, 2015)

In the light of the issues described above, the UN General Assembly adopted a resolution entitled “Decade of Action for Cryospheric Sciences, 2025–2034”, which is dedicated to addressing the challenges associated with changes to the cryosphere through advancement of scientific research and monitoring (UN, 2024). Integrating the ES concept into this discussion may help to better approximate the human wellbeing effects of cryosphere change and incorporate them into decision-making. For instance, quantifying the changes in the cryosphere and resulting alterations in ES provision at different scales has a potential to contribute to a much-needed evidence base on relevant and critical risks in the most vulnerable communities and options to reduce barriers to adaptation and efficient allocation of resources, such as those foreseen by the Warsaw International Mechanism for Loss and Damage associated with climate change impacts (IPCC, 2019; Mechler et al., 2020; UNFCCC, 2025).

4.3 Limitations and further research

The study suffers from several shortcomings. Firstly, the search words used – “cryosphere”, “ice” and “glaciers” did not result in equal coverage of all the components of the cryosphere and is biased towards larger representation of glacier ES and EDS. In hindsight, it would have been more efficient to include each of the components of the cryosphere separated by “OR”

and combining them with “AND ecosystem AND services” to provide a comprehensive coverage of cryosphere’s NCPs. Consequently, the study qualifies as a scoping review not a comprehensive literature review, for which there is still a research avenue. Secondly, as our search focused on the terms “ES” and “EDS”, relevant literature about cryosphere benefits that do not use the ES/EDS terminology may have been missed. For instance, literature on the cultural, spiritual and emotional impacts of glacier retreat that could fit in the category of cultural EDS was not captured through the search, and neither were some of the changing benefits of the permafrost to human wellbeing. Thirdly, the review included review papers, which may pose questions about its added value. However, its main contribution is the systemisation of the existing knowledge on cryosphere’s contributions to people, classification of its ES and EDS according to CICES, and identifying the possible indicators for monitoring of their changes. Including other reviews helped to achieve the principal goal of the scoping review to provide a general overview of cryosphere’s contributions to people. The bias towards glaciers observed in this study is somewhat reflective of the overall bias of the cryosphere literature, which should be taken into consideration in further studies to facilitate better representation of its other components.

As is the case with any study deriving from a literature review, this research is subject to the selection and interpretation bias of the researchers, especially when sourcing and analysing publications. In some cases, it was difficult to make a clear distinction between different types of cryosphere ES, such as water runoff regulation, flood protection, and drought prevention as they all relate to the regulation of water flows through cryospheric storage. Moreover, the distinction between the reduction of ES and EDS is at times blurred, such as in the case of environmental pollution. To address this, ES and EDS that include distinct underlying bio-geophysical processes were listed separately, e.g., as in the case of biotic and abiotic carbon sequestration. Even though this study aimed to provide a general overview of the cryosphere’s contributions to human wellbeing, most likely not all of them were captured, not least because the review focused only on English language studies, the use of limited search queries, and therefore further additions and elaborations are likely to be needed as the list of cryosphere’s NCPs develops.

The study results point to the need for further research in several areas, including more targeted research on indicators for monitoring cryosphere ES/EDS trends over time on appropriate scales; better definition of the processes underlying the ES and EDS provided by its different components; and selecting and applying suitable indicators on a case study basis, where data is available or can be collected. There is also a need for more primary valuation studies of ES and EDS provided by the cryosphere across all value domains and evaluation of the trade-offs between them (Martín-López et al., 2014). Another research avenue revealed in this study is an exploration of changes in ES typologies and spatial dynamics resulting from the geophysical changes in the cryosphere, e.g., through mapping how some ES or EDS act as intermediate ES/EDS and contribute to the final supply of others.

As cryosphere environments are rapidly altered by climate change, there is a need for more studies on the cascading effects on ES and EDS provision. Further research should also explore the options for adaptive management and governance of the cryosphere that takes into consideration their contributions to human wellbeing at local, regional, and global scales. As different stakeholders at the receiving end of cryosphere’s EDS have varying responsibilities and

abilities to cope with its rapid change, more research is needed on the social component of climate change adaptation, e.g., how plural and often incommensurable ES values and power dynamics affect actors' adaptation capabilities (Chapin et al., 2015; Felipe-Lucia et al., 2015). This scoping review serves as one more step towards systemising the knowledge on cryosphere's ES, EDS, and possible indicators for monitoring their trends. The next logical step could be analysing these trends using the suggested indicators and perhaps adding more indicators as has recently been done for some other ES, such as forests (Helseth et al., 2022) and deltaic flood plains (Gómez-Baggethun et al., 2019).

5. Conclusion

This scoping review synthesized knowledge on the cryosphere's contributions to human well-being through the delivery of ES and EDS, using the SALSA literature review methodology and CICES classification. A total of 30 ES and 10 EDS were identified, together with multiple potential indicators for monitoring trends in their changes that can be accounted for in different value domains: biophysical, monetary, and socio-cultural. As cryospheric environments and their capacities to provide vital ES are being increasingly altered by climate change, especially around the poles and in high mountains, and monitoring their changes and human wellbeing impacts can aid decision-making. Despite the changing geophysical structures that underpin cryosphere ES, ice continues to provide vital contributions to people in terms of sustenance, regulating and maintenance of geo-bio-physical balance, and non-material cultural benefits. At the same time, negative contributions of the cryosphere to human wellbeing, such as sea level rise and glacier sedimentation, are augmented by climate change. In the light of the crucial importance of the cryosphere to the ecological functioning of the Earth's socio-ecological systems, there is an urgent need to mitigate climate change, yet the timescales for such action are very large, and adaptation is increasingly necessary. The classification of cryosphere's contributions to people according to CICES provided in this paper is a step towards a better approximation of human wellbeing benefits sourced from it, their changes, and the pathways for securing them.

Acknowledgements

Laura Malinauskaite received funding by the University of Iceland's Research Fund's Post-Doctoral Research Grant (grant number 1533106).

Erik Gomez-Baggethun received partial funding for this research from the FORMAS-funded project *Changing social and cultural values of nature: Exploring plural values of human-nature relationships in glacierized environments* (NATURICE).

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Appendix A

The list of publications sourced for the scoping review

1. Cook et al. (2021)
2. Anisimov et al. (2017)
3. Mukherji et al. (2019)
4. Xiao et al. (2015)
5. Zhang et al. (2022a)
6. Su et al. (2019)
7. Paudel and Andersen (2010)
8. Huggel et al. (2020)
9. Pritchard (2019)
10. ICIMOD (2023)
11. Shugar et al. (2020)
12. Wadham et al. (2019)
13. IPCC (2019)
14. Peter and Sommaruga (2016)
15. Hood et al. (2015)
16. Tian et al. (2019)
17. Rasul and Molden (2019)
18. Milner et al. (2017)
19. Musacchio et al. (2019)
20. Lencioni et al. (2015)
21. Lone et al. (2021)
22. Zhang et al. (2022b)
23. Rasul and Molden (2019)
24. X. Wang et al. (2020)
25. Vincent et al. (2011)
26. Gobbi et al. (2021)
27. Schirpke et al. (2016)
28. Gagné (2019)
29. Kronenberg (2013)
30. Immerzeel et al. (2020)
31. Biemans et al. (2019)
32. Ruiz-Pereira et al. (2023)
33. Pertierra et al. (2021)

Appendix B

CICES classification (version 5.2) of cryosphere geosystem outputs – extended table

Section	Division	Group	Class	Class type	CICES 5.2 code	Service
Provisioning (abiotic/ geophysical)	Water	Surface water used for nutrition, materials or energy	Surface and ground water for drinking	By type or source	4.1.1.1	Freshwater for drinking
Provisioning (abiotic/ geophysical)	Water	Surface water used for nutrition, materials or energy	Surface water used as a material (non-drinking purposes)	By type or source	4.1.1.2	Freshwater for sanitation and irrigation
Provisioning (abiotic/ geophysical)	Water	Surface water used for nutrition, materials or energy	Surface water used as a material (non-drinking purposes)	By type or source	4.1.1.2	Snow and ice material for building and decoration
Provisioning (abiotic/ geophysical)	Water	Surface water used for nutrition, materials or energy	Freshwater surface water used as an energy source	By type or source	4.1.1.3	Cooling
Provisioning (abiotic/ geophysical)	Water	Surface water used for nutrition, materials or energy	Surface water used as an energy source	By type or source	4.1.1.3	Hydropower
Provisioning (abiotic/ geophysical)	Water	Other aqueous ecosystem outputs	Other	By type or source	4.1.X.X	Feed and fodder production enhancement
Regulation and maintenance (abiotic/ geophysical)	Regulation and maintenance of geophysical environment	Regulation of baseline flows and extreme events	Abiotic regulation of liquid flows	By type	5.2.1.2	Water runoff regulation
Regulation and maintenance (abiotic/ geophysical)	Regulation and maintenance of geophysical environment	Regulation of baseline flows and extreme events	Abiotic regulation of liquid flows	By type	5.2.1.2	Flood protection
Regulation and maintenance (abiotic/ geophysical)	Regulation and maintenance of geophysical environment	Regulation of baseline flows and extreme events	Abiotic regulation of liquid flows	By type	5.2.1.2	Drought prevention
Regulation and maintenance (abiotic/ geophysical)	Regulation and maintenance of geophysical environment	Regulation of baseline flows and extreme events	Abiotic regulation of liquid flows	By type	5.2.1.2	Water storage

Regulation and maintenance (abiotic/ geo-physical)	Transformation of biochemical or physical inputs to ecosystems	Mediation of waste, toxics and other nuisances by non-living processes	Mediation of wastes by other chemical or physical means (e.g. via filtration, sequestration, storage or accumulation)	By type	5.1.1.3	Water purification
Regulation and maintenance (abiotic/ geo-physical)	Transformation of biochemical or physical inputs to ecosystems	Mediation of waste, toxics and other nuisances by non-living processes	Mediation of wastes by other chemical or physical means (e.g. via filtration, sequestration, storage or accumulation)	By type	5.1.1.3	Carbon sequestration (abiotic)
Regulation and maintenance (biotic/ biophysical)	Regulation of physical, chemical, biological conditions	Atmospheric composition and conditions	Regulation of chemical composition of atmosphere and oceans	By contribution of type of living system to amount, concentration or climatic/ atmospheric parameter	2.3.6.1	Carbon sequestration (by ice sheet microbial communities)
Regulation and maintenance (abiotic/ geo-physical)	Other types of regulation and maintenance service by living processes	Other	Other	By contribution of type of living system to amount, concentration or climatic/ atmospheric parameter	2.4.X.X	Cycling of carbon and nutrients
Regulation and maintenance (abiotic/ geo-physical)	Regulation and maintenance of geophysical environment	Maintenance of physical, chemical, abiotic conditions	Maintenance and regulation by inorganic natural chemical and physical processes of fresh or salt waters	By type	5.2.2.1	Increased ocean primary productivity through supply of minerals
Regulation and maintenance (abiotic/ geo-physical)	Regulation and maintenance of geophysical environment	Maintenance of physical, chemical, abiotic conditions	Maintenance and regulation by inorganic natural chemical and physical processes	By type	5.2.2.2	Climate regulation
Regulation and maintenance (abiotic/ geo-physical)	Regulation and maintenance of geophysical environment	Maintenance of physical, chemical, abiotic conditions	Maintenance and regulation by inorganic natural chemical and physical processes	By type	5.2.2.1	Water temperature regulation

			of fresh or salt waters			
Regulation and maintenance (abiotic/ geophysical)	Regulation and maintenance of geophysical environment	Regulation of baseline flows and extreme events	Abiotic regulation of liquid flows	Amount by type	5.2.1.2	Groundwater formation and recharge
Regulation and maintenance (abiotic/ geophysical)	Other type of regulation and maintenance service by abiotic processes	Other	Other	By type	5.3.X.X	Load bearing and support provided by ice, frozen ground, and permafrost
Regulation and maintenance (abiotic/ geophysical)	Regulation and maintenance of geophysical environment	Regulation of baseline flows and extreme events	Abiotic regulation of mass flows	By type	5.2.1.1	Erosion, rockfall and landslide protection
Regulation and maintenance (abiotic/ geophysical)	Regulation and maintenance of geophysical environment	Mediation of wastes, toxins and other nuisances by non-living processes	Geological structures and deposits for storage of anthropogenic wastes	By type	5.1.1.4	Environmental pollution regulation
Regulation and maintenance (abiotic/ geophysical)	Other type of regulation and maintenance service by abiotic processes	Other	Other	By type	5.3.X.X	Habitat for endemic species
Cultural (abiotic/ geophysical)	Physical and experiential interactions with biophysical environment	Direct, in-situ and outdoor interactions with geophysical systems that depend on presence in the environmental setting	Characteristics of geophysical systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	By type of geophysical characteristic or environmental setting	6.1.1.1	Recreation and tourism
Cultural (abiotic/ geophysical)	Intellectual and representative interactions with geophysical environment	Direct, in-situ and outdoor interactions with geophysical systems that depend on presence in the environmental setting	Elements of geophysical systems that enable scientific investigation or the creation of traditional	By type of geophysical characteristic or environmental setting	6.2.1.1	Enhancement of scientific and traditional knowledge

			ecological knowledge			
Cultural (abiotic/ geophysical)	Intellectual and representative interactions with geophysical environment	Direct, in-situ and outdoor interactions with geophysical systems that depend on presence in the environmental setting	Elements of geophysical systems that enable education and training	By type of geophysical characteristic or environmental setting	6.2.1.2	Education
Cultural (abiotic/ geophysical)	Intellectual and representative interactions with geophysical environment	Direct, in-situ and outdoor interactions with geophysical systems that depend on presence in the environmental setting	Elements of geophysical systems that enable aesthetic experiences	By type of geophysical characteristic or environmental setting	6.2.1.4	Aesthetics
Cultural (abiotic/ geophysical)	Intellectual and representative interactions with geophysical environment	Indirect, interactions with geophysical systems	Elements of geophysical systems used for entertainment or representation outside the setting concerned	Amount by type	6.3.1.1	Artistic inspiration
Cultural (abiotic/ geophysical)	Spiritual, symbolic and other interactions with geophysical environment	Elements of geophysical systems that are indirectly appreciated and have significance for people without their presence in the environmental setting	Elements of geophysical systems that have sacred or religious meaning	By type of geophysical characteristic or environmental setting	6.4.1.2	Spiritual enrichment
Cultural (abiotic/ geophysical)	Spiritual, symbolic and other interactions with geophysical environment	Elements of geophysical systems that are indirectly appreciated and have significance for people without their presence in the environmental setting	Elements of geophysical systems that have symbolic meaning	By type of geophysical characteristic or environmental setting	6.4.1.1	Community identity
Cultural (abiotic/ geophysical)	Spiritual, symbolic and other interactions	Other biophysical elements of species or ecosystems that are	Elements or features of geophysical systems whose	By type of geophysical characteristic	6.4.2.2	Existence and bequest values

	with geo-physical environment	appreciated in their own right by people	inter-generational existence or conservation is important to people.	or environmental setting		
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