Co-production processes underpinning the ecosystem services of glaciers and adaptive management in the era of climate change

Abstract

Glaciers have been an increasingly studied topic in the ecosystem services (ES) literature, with multiple scientific studies affirming a critical and diverse contribution to human well-being. However, the literature to date on glacier ES has lacked a systematic analysis of their type and the various stages in the formation of glacier ES, including the linkages between biophysical structures and ecological processes to human values, benefits and well-being. This paper begins to fill this gap by (1) detailing the first Common International Classification for Ecosystem Services classification of ecosystem services specific to glaciers; and (2) constructing an ES cascade model specific to the ES of glaciers, integrating four main stages of co-production: value attribution, mobilisation of ES potential, value appropriation, and commercialisation. In both stages, examples from the academic and grey literature are highlighted. Based on a systematic literature review, a total of 15 ES are identified, categorised as follows: provisioning (2), regulation and maintenance (6), and cultural (7). Apart from abiotic regulation and maintenance ES, it is evident that human interventions are necessary in order to mobilise, appropriate and commercialise several glacier ES, including freshwater for drinking, hydropower generation, recreation and education. Rapidly intensifying climate change has led to intense focus on the initial co-production process of value attribution and identification of dynamic ecosystem services potential, with a view to maximising commercial benefits in the coming decades where this is possible, especially linked to hydropower generation from glacial rivers. However, this study also finds that adaptive ecosystem management is a necessary pre-requisite of resilience but may be insufficient in this context to address potential ecosystem disservices and potentially catastrophic impacts to human well-being, such as from dangerous glacier outburst floods.

Keywords: co-production; glaciers; ecosystem services; environmental change; values

1. Introduction

The cryosphere (snow, glaciers, permafrost, lake and river ice) covers approximately 10% of the planet's surface (IPCC, 2019). Seminal publications have stressed the significance of ice-covered landscapes to the quality and functioning of human life, including the Millennium Ecosystem Assessment (MEA, 2005) and the Intergovernmental Panel on Climate Change's Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019). In relation to melting glaciers, the impacts of climate change include various physical and biological ramifications for communities living downstream of major rivers (IPCC, 2019). Although misconceived as an issue of major concern only for communities in the Arctic, the so-called 'Third Pole' region in the Tibetan Plateau, Himalayas, Hindu Kush, Pamirs and Tien Shah Mountains exemplifies the importance of glaciers to human well-being (Chen et al., 2019; Li et al., 2020; Zhang et al., 2019). Including around 100,000 km^2 of glaciers, meltwater from this region provides the source of Asia's largest lakes and rivers, including the Ganges, Yellow and Yangtze, known collectively as the Asian Water Towers (Immerzeel et al., 2020; Zhao & Zhao, 2020). These provide both water and food security and socio-economic sustainability for several nations, supporting a population of nearly 2 billion and a Gross Domestic Product of US$ 12.7 billion (Yao & Xue, 2019).

Iceland's 'funeral for a glacier' and an inscribed letter on a plaque to the people of the future provided an affirmation regarding society's knowledge of the impending challenge (Engel, 2019; Magnason, 2019; Fried, 2020). The anthropomorphic commemoration of the demise of Ok glacier in 2019 was attended by politicians, a United Nations human rights commissioner, scientists and the research community. A poignant image of environmental change was reported by media outlets around the world. The event commemorated the seemingly irreversible passing into non-existence of a feature and shaper of the Icelandic landscape, as well as being a public acknowledgement of the vast and ongoing glacial retreat that is happening on a global scale (Hall & Saarinen, 2020). At the same time, a deeper point was made about human-environment relationships and interactions – the development of fossil reliant economies that continue to exacerbate climate change and rates of glacial melting, and the continued dependency of human beings on glaciers for survivability and economic prosperity (Biemens et al., 2019; Carturan et al., 2019; Sun et al., 2020). According to the IPCC (2019), with high confidence it is evident that shrinking glaciers have already had negative consequences on multiple ecosystem services (ES) related to food security, water resources, water quality, livelihoods, health and well-being, infrastructure, transportation, tourism and recreation, and culture. The costs and benefits are unequal but thought very likely to be more extreme for indigenous peoples (IPCC, 2019).

Ecosystem services practitioners often refer to the interactions in socio-ecological systems as co-production processes, meaning that ecosystem services of benefit to human well-being are not simply received but created via joint production (Fischer & Eastwood, 2016; Palomo et al., 2016). The topic and its underlying theory have received increasing attention in recent years, with emphasis placed on depicting sequential stages in co-production in a variety of resource contexts (Malinauskaite et al., 2021b; Molnár et al., 2020; Palomo et al., 2016; Spangenberg et al., 2014) and the acquisition of understanding concerning how different forms of capital are necessary to actualise well-being benefits (Outeiro et al., 2017; Palomo et al., 2016). Despite the clear links between glacier ecosystems and human well-being, no academic studies have yet explored the subject of how glacier ecosystem services are co-produced. An understanding of capital inputs in the formation of glacier ES, and particularly how these are mobilised and appropriated, is an important basis for determining adaptive management measures in response to environmental change, especially climate-related impacts.

It is also evident that the existing literature on glacier ES is somewhat scattered and piecemeal. Studies have tended to focus on either the impacts of climate change on specific sites (Grima & Campos, 2020; Huggel et al., 2020), the underlying ecological processes (Fragniere et al., 2020; Laurent et al., 2020; Momblach et al., 2020) and supporting ES functions that underpin human well-being (Rogers et al., 2020; Sun et al., 2020), or very specific cultural ES (Wang et al., 2019). No attempt has been made to synthesise existing research and consider the various ways in which glacier ES contribute to human well-being. The two main aims of this paper are thus as follows: (1) to provide the first classification of glacier ES in the academic literature; and (2) to explore the role of co-production processes in the supply and demand of glacier ES. Aim (1) will be fulfilled through the utilisation of the widely adopted Common International Classification for Ecosystem Services (CICES), a useful typology for systemising glacier ES due to its deployment in economic accounting and valuation, and in mapping and designing indicators (Haines-Young & Potschin, 2018). Aim (2) will be explored via analysis of co-production processes depicted in the five-stage ES cascade model of Malinauskaite et al. (2021b). The ES cascade model underpins CICES, ensuring synergy and alignment in the two aims of the paper.

This paper is structured as follows. Section 2 outlines the theoretical framework. Section 3 describes the methodology that was adopted to identify relevant literature on glacier ES, co-production processes and management implications in the context of climate change. Section 4 provides the results, detailing underlying ecological functions and processes of glaciers, before outlining examples of glacier ES and co-production processes in the ES cascade model. Section 5 discusses the main impacts of climate change on glaciers and management implications with respect to co-production. Section 6 provides a brief conclusion and outlines management and research-related recommendations.

2. Theoretical framework

This paper's analysis derives from and is structured according to the theoretical framework of Malinauskaite et al. (2021b) (Figure 1), which integrates the ES cascade model of Haines-Potschin (2010; 2018) and the four co-production processes identified by Spangenberg et al. (2014): value attribution; mobilisation of potential; appropriation; and commercialisation. For readers who are unfamiliar with the nomenclature specific to the co-production literature, Table 1 provides a set of commonly agreed definitions of these processes.

Table 1. Co-production processes in the ES cascade.[1]

Co-production Process	Definition
Value attribution	"Characterised as an intellectual act defining an ecosystem service potential, as a potential supply for an assumed societal (and thus group and culture specific) demand" (Spangenberg et al., 2014, p. 25)
Mobilisation of potential	"Anthropogenically defined and produced, the results of socio-technical systems activating the potentials offered by nature's functions" (Spangenberg, 2014, p. 25)
Appropriation	"The transformation, processing and /or providing of the services to generate ecosystem benefits, again requiring investments of time, work and resources, and money as a means to make them available" (Braat and de Groot, 2012, p.8)
Commercialisation	"Occurs when appropriated ES are sold in markets, i.e. when those who mobilise and/or appropriate ES decide to exchange at least a part of them for money or other goods" (Malinauskaite et al., 2021b, p.6)

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[1] Reproduced with permission from Cook et al. (2020).

One of the advantages of the model of Malinauskaite et al. (2021b) is that it can easily be applied to any resource context involving socio-ecological interactions and the receipt of human well-being via ES. Its application has already been demonstrated recently in two diverse contexts: whale and geothermal ES (Cook et al., 2020; Malinauskaite et al., 2021b). In addition, the model makes it explicit that each stage in the ES cascade model requires inputs of natural capital, but also physical (built and human) in order to escalate to later stages in the cascade (Malinauskaite et al., 2021b; Palomo et al., 2016).

Figure 1 depicts both supply- and demand-side occurrences. The supply-side represents the biosphere; the demand side is the anthroposphere. The supply-side includes the biophysical structure, processes and functions (Haines-Young & Potschin, 2018). They are thus inclusive of the supporting and intermediate ES that are represented in other ES typologies such as MEA (2005) and TEEB (2010). The crossover between supply and demand denotes the ES appropriation stage in co-production. An exception to this concerns regulating and maintenance ES, where human well-being benefits are received directly from the supply-side through ecosystem functions and processes, not necessitating any form of physical capital mobilisation or cognitive interpretation of benefits.

All well-being benefits in Figure 1 are valued on the demand-side with a view to informing decision and policy-making, illustrated by the feedback loop from the anthroposphere to the biosphere. The valuation approach depends on the underlying value, whether it is monetary (utilitarian) or socio-cultural. Biophysical values are not valued in the model as these relate only to the ecological processes and functions of the ecological infrastructure that lead to the supply of glacier ES. The model identifies that economic valuation can be applied to estimate the value or changes in monetary value associated with the use and non-use dimensions of Total Economic Value. In this regard, policy- and decision-making can be informed by either using market exchange data or non-market valuation techniques, especially in tools such as Cost-Benefit Analysis. The model demonstrates that often market exchange data can be utilised when the co-production process of ES commercialisation applies, however, it must be emphasised that non-market valuation techniques are also frequently applied by environmental economists in the absence of market exchange data. Socio-cultural valuation can be applied to any glacier ES as an alternative to economic valuation, particularly when the socio-cultural context involves mixed or non-monetary economies.

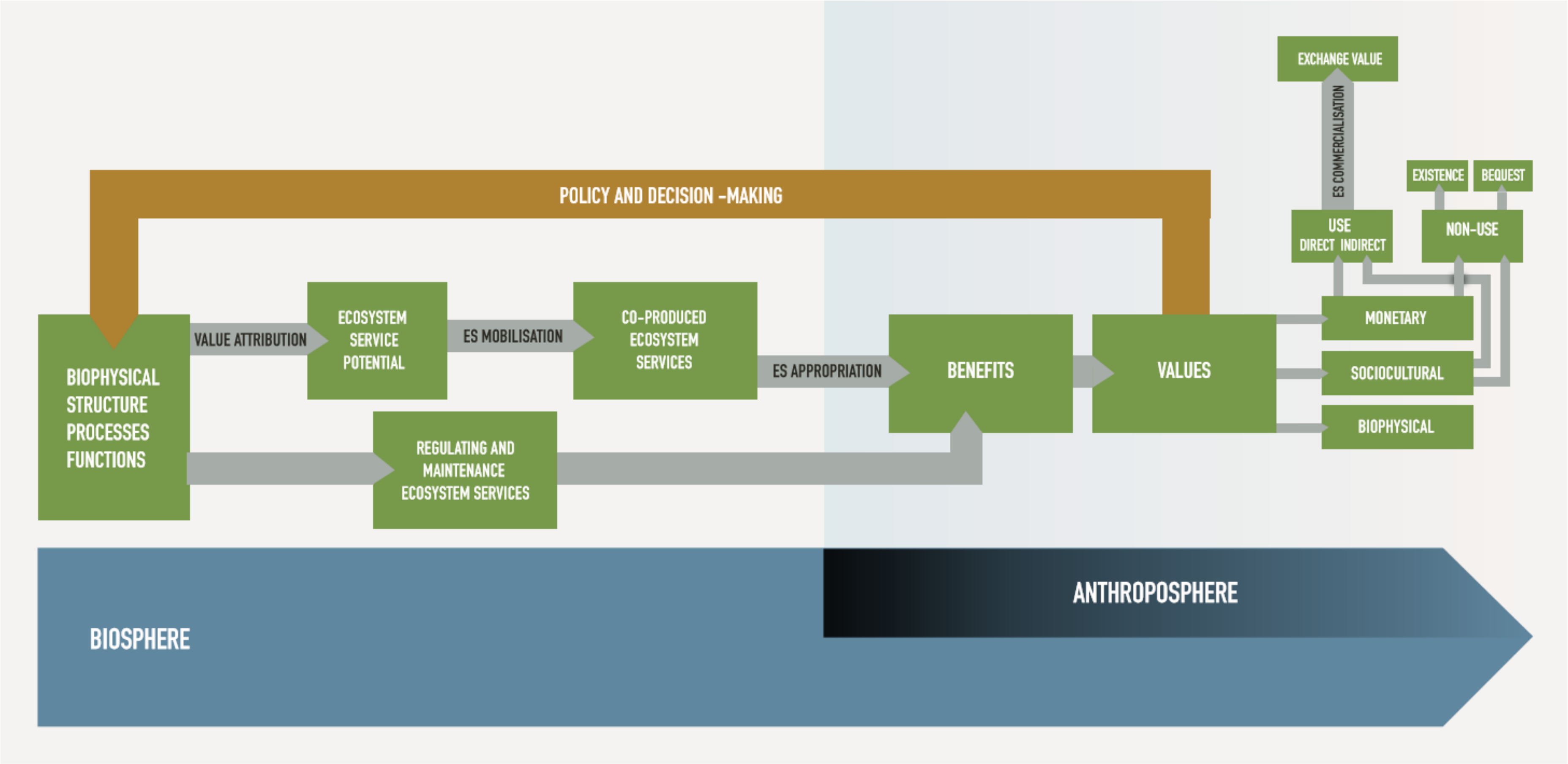

Figure 1. ES cascade model including co-production processes.[2]

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[2] Sourced with permission from Malinauskaite et al. (2021b).

3. Methodology

A systematic literature review was conducted using the Search, Appraisal, Synthesis and Analysis (SALSA) framework. This has been applied recently in a broad variety of contexts, including literature reviews on Arctic ES (Malinauskaite et al., 2019) and the cultural ES of geothermal areas (Cook et al., 2019), and indicators of sustainable energy development (Gunnarsdóttir et al., 2019).

The main stages in the method were conducted as follows:

1) Search
    - Initial search using terms “ecosystem services”, “glacier”, “climate change”, “management” and “planning” and standard BOOLEAN search strings (i.e. AND/OR) in four academic databases (Science Direct, Scopus, Web of Science and Google Scholar) in November 2020. This resulted in a very large set of publications of 12,500 in total, many of which were not relevant to this study.
    - Narrowed search using combinations of initial search terms in conjunction with co-production terminology or synonyms for the processes outlined in Fig. 1: value attribution, ES mobilisation, ES appropriation, and ES commercialisation. For example, in the case of ES commercialisation, terms such as “revenue”, “profits”, “net present value” and “market” were used in conjunction with the initial search terms. After removing duplicate studies, this resulted in a total of 254 publications, including Scopus (n = 96), Web of Science (n = 31), Science Direct (n = 40) and Google Scholar (n = 87).
2) Appraisal
    - All abstracts and conclusions were read in full to determine relevance to this study. Relevant studies were included on the basis that they appeared to address either (a) ecological phenomena in glaciers that could support the supply of ES, (b) co-production processes in the delivery of glacier ES, (c) identification of glacier ES, (d) climate change impacts to glacier ES, or (e) management and planning related implications concerning item (d). Publications focused in general on cryospheric ES, non-specific to glaciers, or those addressing general climate change impacts to glaciers with no consideration of human well-being implications were rejected at this stage.
    - A total of 124 publications were selected to be read in full.
3) Synthesis
    - Each of the selected publications was reviewed with respect to topic and scope.
    - Key outcomes were noted whenever any of the following applied: (a) glacier ES discussed, (b) co-production processes, (c) impacts and risks of climate change, and (d) management implications.
4) Analysis
    - Analysis of key outcomes, structured in accordance with the theoretical framework of Malinauskaite et al. (2021b) in Fig. 1, and responding to the two aims of this paper set out in Section 1.

4. Results

The results first articulate some of the underlying ecological functions and processes of glaciers that underpin the supply of glacier ES. Examples of glacier ES are then reported in Section 4.2.

The various ES cascade stages and connecting co-production processes are illustrated in Sections 4.3 and 4.3, respectively.

4.1 Glacier ecosystems and underlying functions and processes

Glaciers are sometimes considered to be dynamic but cold and lifeless abiotic ecosystems. However, micro lifeforms and organisms are also common despite cold temperatures, limited water for cellular processes and sometimes low nutrient availability (Hotalling et al., 2017). Stibal et al. (2012) describe how the supraglacial ecosystem on the surface of glaciers includes several important habitats. Foremost among these are glacier algae, which form on the upper ice layer (Anesio et al., 2017; Stibal et al., 2020). The abundance of surface life on mountain glaciers can be substantial with algal cell concentrations ranging from 4.4 x 10^4 to 9.9 x 10^5 cells per ml^{-1} of meltwater (Takeuchi, 2001). Cryoconite holes, cylindrical depressions formed by surface melting, provide oases which are home to various microorganisms, including bacteria, algae, annelids, insects and crustaceans (Zawierucha et al., 2015). In addition, high-elevation nesting birds, such as the grey-crowned rosy finch in North America, feed on ice annelids when rearing their young (Stibal et al., 2020).

Many of the ecological processes and functions of glaciers that underpin the supply of final ES occur in the englacial and subglacial zones (Hotalling et al., 2017). Initially via moulins, crevasses and small interstitial spaces in the englacial zone, and then through fracturing in the subglacial zone, meltwater channels facilitate the supporting ES of water cycling, nutrient cycling, dissolvement of atmospheric gases, and glacial till and moraine formation (Chandler et al., 2020; Grau Galofre et al., 2017; Hotalling et al., 2017). These channels provide a conduit from the glacier to glacial streams, rivers and lakes, and their extent varies according to the ambient temperature and level of solar radiation (Hotalling et al., 2017; Marsh, 2017). Kanna et al. (2018) found that subglacial discharge from Bowdoin Glacier in Greenland included nutrient-rich deep water and sediments, plankton and small fish, facilitating primary production in a coastal fjord and providing a feeding area for seabirds and marine mammals.

4.2 Final ES of glaciers

Selected examples from the literature on glacier ES are specified in Table 2, which are classified according to their CICES section and class. A full CICES classification based on section, division, group, class, class type and services is provided in Table 3 in the Appendix.

Table 2. Examples of final glacier ES.[3]

Section	Class	Service	Examples from literature
Provisioning (abiotic)	Surface water for drinking	Freshwater for drinking, sanitation and irrigation	The Third Pole region in Asia supplies the drainage basins of the Ganges, Yellow, Brahmaputra and Yangtze rivers, currently supplying freshwater to nearly 2 billion people (Davies, 2020). Melting glaciers provide approximately 1.8 trillion litres of water each summer in Washington State in the United States of America (NSIDC, n.d.). Biemans et al. (2019) highlighted the importance of meltwater for food supply on the Indo-Gangetic plane, where in the pre-monsoon season up to 60% of total irrigation withdrawals derive from mountain snow and glacier melt, contributing an additional 11% to crop production.
Provisioning (abiotic)	Freshwater surface water used as an energy source	Hydropower	Around 55% of Swiss electricity production is currently derived from hydropower (Swiss Federal Office for Energy, 2018), with all large Swiss rivers influenced to some extent by meltwater from glaciers and snow cover. Similar increases in inflow have been observed in Iceland, which derived 73% of its electricity generation from hydropower in 2019 (NEA, 2020).
Regulation and maintenance (abiotic)	Liquid flows	Flood protection	Glaciers provide a valuable role in flood protection through timely discharge of meltwater, thus shielding downstream communities from the risks of dangerous glacial outburst floods (Harrison et l., 2018; Huggel et al., 2020).
Regulation and maintenance (abiotic)	Liquid flows	Water storage	Glacial lakes provide water storage in lakes and reservoirs. The study of Shugar et al. (2020) mapped 254 glacial lakes around the world in the period 1990 to 2018, discovering that global glacial lake volume increased by around 48% to 156.5 km^3.
Regulation and maintenance (abiotic)	Mediation by other chemical or physical means (e.g. via filtration, sequestration, storage or accumulation)	Water purification	Glen et al. (1977) and Shreve (1972) discussed how snow often contains impurities which become incorporated into glaciers. However, during crystallisation, the impurities are trapped by grain boundaries and residual meltwater travels through a tiny vein network in the ice, resulting in purer ice. Glaciers are renowned for some of the purest drinking water in the world (Watson & Lawrence, 2003).
Regulation and maintenance (biotic)	Regulation of chemical composition of atmosphere	Carbon sequestration	The algae and bacteria present on glaciers provide a carbon sequestration function. The study of Anesio et al. (2009) calculated that microbial activity in cryoconite holes in the world's glacier areas outside of Antarctica could fix up to 64 Gg of carbon dioxide emissions per year.
Regulation and maintenance (abiotic)	Maintenance and regulation by inorganic natural chemical and physical processes	Climate regulation	Glaciers help to regulate the climate through the albedo effect, whereby their mainly white surface reflects rather than absorbs solar radiation, leading to a relative reduction in ambient temperatures (Musacchio et al, 2019).
Regulation and maintenance (abiotic)	Maintenance and regulation by inorganic natural chemical and physical processes	Water temperature regulation	Cold water flows from glaciers facilitate water temperature regulation which is of importance to several aquatic species in high-elevation environments. These include aquatic insects (Lencioni et al., 2015), species which are particularly sensitive to stream temperatures and unable to survive without the cooling contribution of glacial meltwater, and various fish species, including trout and salmon (Prosser et al., 1970; USGS, n.d.).

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[3] Note that version 5.1 of CICES does not currently include cultural (abiotic) services in relation to indirect, indoor educational experiences. However, experiences in glacier museums and visitor centres also constitute a form of education, in addition to traditional outdoor forms of education through guided hikes and climbs on the glacier, and boat and kayaking trips on glacial lakes. In addition, spiritual enrichment may occur through direct interactions with glaciers, such as in-situ meditations, visionary experiences and a variety of personally transformative experiences.

Section	**Class**	**Service**	**Examples from literature**
Cultural (abiotic)	Natural, abiotic characteristics of nature that enable active or passive physical and experiential interactions	Recreation and tourism	Recreation and tourism linked to glaciers are of considerable economic value around the world. A study by the National Park Service in the United States found that the Glacier National Park in Montana received nearly 3 million visitors in 2018, who collectively spent \$US 344 million in communities near the park, supporting 5,230 jobs and providing a cumulative benefit to the local economy of \$US 484 million (NPS, 2019). A travel cost study on Yulong Snow Mountain in China, the nation's most popular glacier tourist attraction, identified consumer surplus in 2016 in the region of 656-3,439 CNY, and total recreational value of 1.97-8.17 billion CNY (Yuan & Wang, 2018).
Cultural (abiotic)	Natural, abiotic characteristics of natural that enable intellectual interactions	Education	Glaciers form the focus of many courses in secondary and tertiary education around the world and a focal point of dedicated establishments such as the Glacier Institute in the United States (Glacier Institute, n.d.). Less formal educational experiences occur for individuals during recreational experiences on glaciers or glacial lakes and visits to national park or World Heritage visitor centres in areas where glaciers are prevalent (Welling et al., 2015). Recognising the educational opportunities of glaciers and the number of tourists seeking ice-themed adventures, Ilulissat in Greenland is developing a new Icefjord Centre to serve its World Heritage Site at Jakobshavn Glacier (DAC, 2018).
Cultural (abiotic)	Natural, abiotic characteristics of natural that enable intellectual interactions	Aesthetics	The beauty of glaciers and the everchanging features of ice formations ensure that they are valued for reasons of aesthetics. This has been demonstrated in academic studies on landscape value. Schirpke et al. (2016) included an aesthetic value survey of 10,215 viewpoints along hiking trails in the Central Alps of Austria and Italy. The viewpoints considered to have the highest aesthetic value were those of highest altitude with unimpeded vistas of lakes and glaciers.
Cultural (abiotic)	Natural, abiotic characteristics of the environment that enable spiritual, symbolic and other interactions	Artistic inspiration	Rossi et al. (2020) highlighted an exposition of artistic pictures aimed at documenting the impacts of climate change on glaciers. Rathwell & Armitage (2016) described how artistic expressions can help to bridge knowledge gaps regarding socio-ecological change between indigenous and non-indigenous peoples in Arctic Canada. Glaciers have formed the subject of paintings (Magnússon, 2017), poems (Alley, 2020), songs (Gagné, 2020) and featured as a central theme in books and film adaptations, such as 'Under the Glacier' by Halldór Laxness, a Noble Prize-winning author (Egeler & Gropper, 2020).
Cultural (abiotic)	Natural, abiotic characteristics of the environment that enable spiritual, symbolic and other interactions	Spiritual enrichment	Glaciers provide an important source of spiritual enrichment for many individuals, communities and indigenous peoples, representing symbols of power and the sacred (Allison, 2015). Sherry et al. (2018) found connotations of the sacredness of place and desire for cultural continuity in a glacial valley in Nepal, a short distance downstream from the dangerous Tsho Rolpa glacial lake. Vuille et al. (2018) discussed how water management practices linked to glacial rivers in the Andes are shaped by cultural belief systems and spiritual practices.
Cultural (abiotic)	Natural, abiotic characteristics or features of nature that either have an existence or bequest value	Existence and bequest values	Many glaciers are associated with existence and bequest values due to perceptions of their importance, increasing scarcity and multiple contributions to human well-being. Kronenberg (2013) reported on how proposals to remove 0.8 m^3 of ice from the Pascua-Lima glacier in Chile and Argentina were met with widespread protests, not merely by nationals but also overseas pressure groups and other stakeholders. Vander Naald (2020) explored this topic through a willingness to pay study to slow glacier loss in Alaska. Participants in choice experiments were willing to pay a mean of US\$ 648 over a 60-year period to reduce the annual rate of glacier loss to 0.15 km^3.
Cultural (abiotic)	Other	Community identity	Many places experience a sense of community identity tied to nearby glaciers (Jurt et al., 2015), even more so when they are reliant on the feature for their survival and livelihoods (Bonnett & Birchall, 2020). MacKinnon (2016) described how the retreat of the Comox Glacier on Vancouver Island, Canada has undermined the sense of local identity and caused doubts to emerge about the meaning of place.

4.3 Glacier ES – cascade stages

4.3.1 Biophysical structure / process / function

These aspects are summarised in Section 4.1 and are not duplicated here for reasons of space.

4.3.2 Ecosystem service potential (ESP)

At this stage of the ES cascade, the ES of potential value to human well-being are identified by actors with the resources and capabilities to secure their utilisation (Cook et al., 2020; Malinauskaite et al., 2021b). They include the identification of sites of likely value for tourist and educational experiences, and consideration is given to how the location of architectural design is central to the visitor experience, for example, the new Ilulissat Icefjord Visitor Centre (DAC, 2018).

In the ESP stage, the emphasis is on the identification of prospectivity and initial planning, with a view to then mobilising significant capital resources – physical, financial and human – in the event of a positive assessment of potential and/or receipt of necessary planning permissions. Often such initiatives and modelling of potential can be driven by a need to fulfil community-specific policies – for example, the desire to expand the limited facilities for tourists in Ilulissat, the most popular tourist hub in Greenland (Ionnidesdv, 2019). Sometimes there can be a need to provide more electricity to satisfy economic objectives linked to industrial expansion, as has been evident in the harnessing of some of Iceland's glacial rivers for hydropower in the past (Olafsson et al, 2014). Equally, glaciers are heavily influenced by climate change impacts in a negative way, but broader policy objectives related to its tackling can underpin the ESP stage.

4.3.3 Co-produced ecosystem services

Except for regulating and maintenance services, the ES outlined in Table 2 require human agency in order to be mobilised, appropriated and, in some cases, commercialised.

4.3.4 Benefits

Many well-being benefits are received by human beings from glaciers, the majority requiring direct physical and/or cognitive interactions between the biosphere and anthroposphere. Provisioning ES require large physical capital contributions in terms of infrastructure. In the case of hydropower plants, these include in many cases the damming of glacial lakes and rivers, alongside the construction of capital-intensive power plant facilities (Williams, 2020). The drinking of freshwater from glacial rivers may be a very direct experience in some parts of the world, but equally it can be more capital-intensive and necessitate water treatment works and pipe distribution networks (Falkland and White, 2014).

Disentangling the tangible infrastructure from cognitive aspects of well-being is complicated in this context, since glaciers provide an aesthetic contribution, but dammed glacier lakes also do so (Farinotti et al., 2016). Many of the cognitive benefits are directly related to the glacier itself, such as artistic inspiration, recreational experiences, and appreciations corresponding to non-use value. The facets of proximity, power, magnificence, radiance, beauty and rarity often underpin such appreciations, and unlike most ecosystems, which are rather static, an in-presence sense of dynamics contributes to the allure. Brooke & Williams (2020) discussed how the aesthetics of Icelandic glaciers can even have a therapeutic role, contributing to physical, mental, and emotional healing.

4.3.5 Value

As discussed in relation to Figure 1, different values underpin the formation of well-being benefits, two of which are subsequently valued: monetary and socio-cultural. This is not to say that underpinning biophysical values are unimportant – on the contrary, many ecological functions and processes are critical to vital ES, such as water storage and climate regulation, and the facilitation of primary production and downstream biodiversity (Cauvy-Fraunié & Dangles, 2019). Two key issues influence the values specific to a glacier ES: (1) whether the value was formed on an individual or collective basis; and (2) the socio-cultural and socio-economic context specific to the location. Well-being benefits for individuals, whether they belong to the monetary or socio-cultural domain, can be received either directly or indirectly. These include the meeting of fundamental needs through provisioning services – drinking water and hydropower in the case of glacier ES. However, although these will often reflect a monetary value in Western economies, this is not likely to be true everywhere. Peoples reliant on glacial freshwater as an input for subsistence agriculture (Biemens et al., 2019), or societies operating with mixed or non-monetary economies, may be more likely to value provisioning services socio-culturally. Paid recreational and educational experiences involving glaciers will be more likely to only reflect a monetary value (Yuan and Wang, 2018), since an entry fee represents a barrier to entry for non-monetary societies.

Existence and bequest benefits are perhaps more likely to derive from collectively formed socio-cultural values, as these can be underpinned by concerns for others in society to have an opportunity to experience glacier ES (Kronenberg, 2013). Indigenous peoples who cultivate spiritual practices or sacred land associations linked to glaciers are highly likely to value glaciers socio-culturally rather than monetarily. This is probably much more due to the collective cultural formation of the benefit as it is the operation of a non-monetary society. However, socio-cultural values can resonate in monetary societies, for instance in Table 2's example of the people living nearby to the diminishing Comox Glacier and their uneasy consciousness about what this means for their sense of space and place (MacKinnon (2016).

4.4 Co-production processes involving glacier ES

4.4.1 Value attribution

Value attribution is the first co-production stage linking ecological infrastructure, functions and processes to ESP. It assumes or relies upon an already identified societal demand for an ES. The process of identifying prospectivity (ESP) can include a range of feasibility techniques, which will vary greatly according to the specific glacier ES. Hydropower potential is normally established through computer simulation modelling to determine likely energy generation and what this might imply for future infrastructure needs, such as number of turbines, installed power, and turbine design flow rate (Koc et al., 2016; Kuriqi et al., 2019). The strategic determination of sites of likely high value for recreational and educational glacier experiences is a complicated process involving formal and informal assessments of aesthetic value, access potential, health and safety issues such as potential rockfalls (Purdie et al., 2015) and floods (Allen et al., 2016), and how all of these issues might be influenced by climate change dynamics in the future (Garavaglia et al., 2012; Welling et al., 2015).

4.4.2 Mobilisation of ESP

the case of hydropower projects, mobilisation will involve a series of capital-intensive steps, including the securing of sufficient financing; full planning applications based on working rather than planning drawings; advanced engineering work to design all aspects of power plant infrastructure; the undertaking of various technical reports as required by planning laws (e.g.

Environmental Impact Assessments); and extensive consultation with locally impacted stakeholders (Greacen & Palettu, 2007; Singh, 2020). All these aspects are typically necessary for successful license applications to permit facilitation of new access provision and the construction of power plant infrastructure and upstream dams.

Similar but somewhat less capital-intensive processes are involved in the development of recreational and educational facilities tied to glaciers. Museums and visitor centres require funding support for exhibits to be planned and buildings either to be constructed, rented or a change-of-use facilitated. Equally, even companies offering recreational experiences such as glacial hikes need to consider the location and design of storage buildings for essential gear, such as ice picks, crampons and helmets, and where on-site ticketing, restroom and café facilities will be positioned (Welling et al., 2019). In the case of visitor centres and museums, health and safety considerations will likely involve facilitating easy access for disabled persons. In addition, careful planning will need to occur regarding how the needs of people from different backgrounds will be met, especially regarding language issues (Welling et al., 2015). At this stage, human capital is increasingly relevant, not least because of a management need to acquire highly trained staff to lead recreational experiences, for example, glacier hikes, glacier caving and aquatic adventures on glacial lakes (Welling et al., 2015; Welling et al., 2019).

4.4.3 ES appropriation

After the detailed planning stage, once all necessary licensing approvals have been secured, the construction of essential access, and plant and ancillary infrastructure (e.g. transmission lines for hydro-electricity), commences with respect to provisioning ES and the cultural ES necessitating visitor facilities. This is the often very long process of ES appropriation, where the biosphere and anthroposphere overlap and human well-being benefits can begin to be actualised. In addition to major infrastructure construction, the ES appropriation stage could also involve a series of minor physical capital interventions into the landscape, for example, the construction of hard-wearing footpaths to reach new glacier viewpoints (Ionnidesv, 2019).

4.4.4 ES commercialisation

ES commercialisation involves the exchange of money or other resources for appropriated ES benefits. In the context of glacier ES, this could involve market sales of electricity and cold water to households, the government and commercial entities. Additionally, commercialisation could occur through the sales of tickets for glacier-themed experiences: hikes, climbs, expeditions, sightseeing boat trips, caving, kayaking, museum tours, special cinematic and artistic exhibits in visitor centres etc (Greacon and Palettu, 2007; Kuriqi et al., 2019; Welling et al., 2019).

5. Discussion

5.1 Physical and ecological impacts of climate change on glaciers

Several severe risks may occur due to climate change that undermine the functioning of glaciers, reducing ecosystem resilience and potentially resulting in loss of ES or ecosystem disservices. The IPCC (2019) observed a very likely mass loss of glaciers of 490 (+/- 100) kg/m^2/year in all mountain regions excluding the Canadian and Russian Arctic, Svalbard, Greenland and Antarctica. This has increased the frequency and magnitude of natural hazards, led to a decline in agricultural yields in the Hindu Kush Himalayan region and the tropical Andes, and had some impacts on hydropower operations (IPCC, 2019). These impacts and others can be expected to increase and further intensify in the future, since the IPCC (2019) projects show that compared to the period 1986-2005, low elevation snow depth is likely to decrease by 10-40% for 2031-2050, regardless of the Representative Concentration Pathway (RCP), and reductions could be as high as 50-90% for $RCP_{8.5}$ in the period 2081-2100.

The study of Stibal et al. (2019) highlighted the importance of glacier ecosystems to biodiversity and ecosystem functioning. The authors described how temperature and tropical glacier ecosystems are particularly vulnerable to climate change, which is of considerable concern given limited knowledge of their biodiversity, especially endemic taxa. Zawierucha & Shain (2019) concluded that the only way of conserving temperate and tropical glacier biota is likely to be within cultural collections, given the impossibility of habitat restoration. Hotalling et al. (2017) made similar assertions to Stibal et al. (2019), reiterating that microbial life is the most powerful geochemical force in extreme, ice-based ecosystems, and calling for more research into the role that glaciers play in geomicrobiological, biogeochemical and ecological processes.

Glacier ecosystems themselves provide only a small contribution to carbon sequestration through algae and other bacteria (Hotalling et al., 2017). However, in much the same vein as the contribution of glacier ES to agricultural production, glaciers provide indirect inputs of considerable value via their contribution to downstream regulation and maintenance ES. Tropical mountain wetlands in the high Andes of Colombia can store a mean of 1,200 tonnes of carbon per hectare (Benavides et al., 2013). Thus, loss of glaciers and access to inflows from glacial rivers will result in the transformation of wetlands from carbon sinks to carbon sources (Benavides et al., 2013; Hribljan et al., 2016).

Given the near certainty of further glacier shrinkage, it is necessary to consider the management responses that are appropriate for fulfilling the requirement of Sustainable Development Goal 15 (Life on Land) to ensure the conservation, restoration and sustainable use of all land-based ES (UN, 2015). Most likely, adaptive rather than mitigative management will be necessary, the former recognising the inevitability of environmental change, hazards and risk. This implies that it not only considers the final glacier ES of benefit to human well-being, but also the role of glaciers as intermediaries in the production of other, final ES, such as provisioning services in the agricultural and marine sectors. Climate change may lead to adaptive management costs and new benefits, both of which have implications for co-production processes in order to sustain or enhance the flow of the ES cascade. The remainder of this section considers some of the already reported impacts of climate change on glacier ES, with the analysis focusing particularly on how co-production processes are affected.

5.2 Climate change, co-production processes and management implications

Two overarching themes emerged from this study's review, both of which have management implications:

1. Intense focus on value attribution and identification of dynamic ESP, with a view to commercialising cases of expanded ESP over the next few decades and pinpointing likely lost benefits.
2. Increased risks and likelihood of ecosystem disservices, including to catastrophic levels, that could potentially destroy the supply of a glacier ES and/or present risks to human well-being that necessitate adaptive management.

5.2.1 Intense focus on value attribution

There is evidence of increased value attribution efforts to comprehend the enhanced ESP of glaciers in the short to medium term with respect to hydropower production. A study by Landsvirkjun, the national power company of Iceland, and the Icelandic Met Office found that in the year 2015 water flows were 10% higher than predicted using historical climate records, and that a further increase in inflow rates of 15% was likely over the period 2015-2050, prior to decline in the period 2068-2020 (Landsvirkjun and Icelandic Met Office, 2018). In addition, the study by Schaefli et al. (2019) reported that glacier mass loss due to climate change has already increased the Swiss national generation of electricity by 3-4% in the period 1980-2018, however, this share is projected to decrease in the period 2040-2060.

There is some evidence that increased ESP is already driving further ES mobilisation and increased ES commercialisation. In some cases, a revenue ‘boom and bust’ potential is evident due to climate change. The Mauvoisin hydropower plant in Switzerland receives glacier meltwater from nine glaciers. Gaudard et al. (2016) have projected that revenue is expected to increase from between $US 87.5-104.3 million in the period 1981-2010 to between US$ 87.5-18.6 million in 2021-2050 due to extra runoff potential. Thereafter, in the period 2071-2100, revenue is projected to fall to between $US 74.0-91.3 million due to advanced glacier retreat. The case of Switzerland’s largest glacier, the Great Aletsch, illustrates a potential race to mobilise capital and appropriate ES benefits during the current phase of climate change. Rack (2020) reported that the company, Alpiq, is planning to utilise a glacial valley that is expected to become ice free in the next 10-15 years, constructing a new power plant that could produce up to 100 GWh of electricity per annum.

The assessment of Landsvirkjun and the Icelandic Met Office (2018) found that the Icelandic hydropower system has to date been able to utilise all of the additional 10% of water inflows from glacier meltwater compared to historical climate records. However, a further increase of 15% is projected by 2050, and of this, only 15% could currently be utilised. In order to appropriate the benefits of increased flow rates, capital-intensive and costly modifications will be necessary to enlarge installed turbine capacity and reservoir storage. Without these adaptations, spills will occur through the water spillways. Increased reservoir storage would also induce a co-benefit in the form of enhanced flood protection. However, these are not swift adaptations. According to Landsvirkjun and Icelandic Met Office (2018), it took four years for the power company to use corrected flow series (accounting for climate change) in reservoir management, and thereafter a two-year period to install extra capacity at their hydropower station in Búrfell. This is somewhat in contrast to the planning approach in Switzerland, which has systemised the accelerated identification of new ESP through its National Research Program on Sustainable Water Management under the project ‘New lakes in glaciating high mountain areas: climate-related development and challenges for sustainable use’ (Terrier et al., 2011).

Increased value attribution is also sometimes apparent in glacier tourism, leading to the anticipation of new and enhanced ESP over the next few decades. Serquet & Rebetez (2011) discovered that summer heat waves in the Swiss Alps have increased the number of nights that tourists spend in alpine resorts. The study of Scott et al. (2007) predicted that there would be an increase in tourism of 36% by 2050 in the Canadian Rocky Mountains, but a decline after 2080 due to glacier disappearance and related ecosystem change. There are also contrasting reports of already reduced ESP due to climate change, leading to more costly mobilisation of physical capital and reduced or lost commercial benefits. In addition to traditional glacier hiking and climbing activities, glaciers often provide a location for year-round skiing, such as in the Austrian and Swiss Alps (Milner et al., 2017). Orlove et al. (2008) reported glacier mass decline of two-thirds at the Vedretta Piana in Italy, leading to falling visitor numbers and a need to redistribute snow from the accumulation zone to fill in crevasses. Other adaptation measures can be more complicated and costly. These include the migration of ski areas to higher elevations and greater use of artificial snow-making technologies, which as long ago as 2007 cost $US 400 million per annum to operate in Switzerland (Matasci, 2012). On some occasions, summer glacier skiing has been completely abandoned in parts of the Alps because of newly emerging safety issues (Falk, 2016).

Welling & Abegg (2019) discussed the adaptation process of tour operators in south-east Iceland. Based on semi-structured interviews with the managers or owners of nine tour companies in the region, the authors reported that the interviewees all viewed climate change as a real phenomenon that affected their business. Adaptive management tended to be short-term and ad hoc based on risk perceptions, self-organisation, and some degree of consultation with hazard reduction institutions. A follow-on study in the region found that participatory scenario planning concerning plausible glacial land cover and land use in the future could be a useful tool for supporting adaptive recreational land-use planning (Welling et al., 2019). From the perspective of the demand-side, a further study by Welling et al. (2020) identified that glacier recession will lead to changes in the accessibility, safety and amenity of many popular glacier tourist destinations in Iceland, which may negatively impact the number of tourists visiting these areas.

Other concerns linked to dynamic ESP involve the role of glaciers in providing meltwater for irrigation and agricultural production. Milner et al. (2017) described several instances of severe economic consequences of climate change-induced alterations to these flows, which are more extreme in dry or semi-arid landscapes. Wang et al. (2014) conducted an evaluation of 446 glaciers in the semi-arid Tien Shan region of China, finding that a 20% reduction in glacier volume over the period 1964-2004 is already negatively impacting agricultural production. Ortiz (2011) reported on drinking water concerns in the Andes of Peru. In the Andean region, nearly 10 million people depend on water from glaciers and large cities for irrigation, including those living in the capital of Lima. Approximately 30% of the Andean ice surface is projected to melt in the next few decades, with increased flows in the short term followed by a tipping point after a few decades, with severe water shortages being likely. Huss & Hock (2018) reported that the tipping point has already been reached for half of the 56 drainage basins they modelled worldwide, after which the volume of freshwater begins to decline, and they cautioned that there is considerable potential for water-based conflicts to emerge between peoples.

Yao et al. (2020) examined the implications of climate warming and cryosphere system changes in the Third Pole. The authors reported that more than 40% of the total runoff of the Trim River comes from glacier meltwater, and that although the area of glaciers in the Trim Basin has shrunk, meltwater runoff increased over the period 1961-2016. Huss & Hock (2018) found that peak water in the large river basins in the Third Pole will most likely be reached in the period 2030 to 2050 but decline thereafter. These types of effects have important management implications in terms of ensuring sufficient water storage over the longer-term, since the downstream regions of the High Himalaya have escalating demands for water, due in part to rapid population growth (Yao et al., 2020). Eventual decreases in glacial runoff would reduce irrigation water availability and agricultural productivity, threatening food security for 4.5% of the population in the Brahamputra, Indus, Yangtze and Ganges basins (Immerzeel et al., 2010). Momblanch et al. (2020) applied a water resources system modelling approach to evaluate ecosystem services provisioning across a range of plausible future climate change scenarios in a Himalayan river system. The authors found that the current and future levels of ES depend greatly on the spatial patterns of climate change and impacts of infrastructure management on river flows. However, even a robust and broad-ranging adaptation strategy was not quite able to bring the quantity of ecosystem services back to baseline levels. This included an optimised irrigation schedule for rice based on soil moisture deficits, the commissioning of new run-of-river hydro power plants designed with climate impacts factored in, and afforestation of bare soil areas in medium to high elevation bands with seasonal snow cover. The authors determined two key findings: (1) adaptation is unable to address losses in climate-dependent ES, such as flow regulation and cultural ES provided by glaciers in the Himalaya; and (2) the ability of adaptive management measures and nature-based solutions to fully negate climate impacts declines as the magnitude of climate change increases. A recent climate change impact study on retreating glaciers in the Spanish Pyrenees identified a likely water deficit challenge in the next thirty years, affecting individuals and industries, which would necessitate similar interventions to those studied by Momblanch et al. (2020): private and public sector financing, human innovation in agricultural practices, and the promotion of alternative consumption activities (Grima & Campos, 2020).

5.2.2 Increased risks and ecosystem disservices

Melting glaciers undermine the protective benefits of glaciers, increasing the likelihood of disasters, potentially to a catastrophic scale. Yao et al. (2020) reported increases in glacier-related disasters due to climate change, highlighting two ice collapses in 2016 in the Aru Range of the Third Pole that led to nine human casualties and the loss of hundreds of livestock. Additionally, glacier collapse in October 2018 blocked the flow of the Yarlung Zambo River in the Third Pole, temporarily reducing flows of downstream ES. Haerberli et al. (2017) charted the increasing risks of landslides from degrading, deglaciated landscapes. Benn et al. (2012) focused on the increasing likelihood of glacial outburst floods from outlet glaciers in the Mount Everest Region. The risk of glacial outburst flooding was also the main topic in the studies of Cook et al. (2016) and Zaginaev et al. (2016) on glacial change in the Bolivian Andes and Tien Shan, respectively. These risks can also lead to conflicts – for example, Huggel et al. (2020) described how Lake Palcacocha in the Andes of Peru is already the focus of a prominent legal case concerning the increased risk of flooding due to climate change.

Sometimes infrastructure-related adaptations to climate change can be almost prohibitively expensive, reducing the capacity to adapt. Rasul & Molden (2019) reported that the adaptation cost of reducing flood risk by digging a canal into the Tsho Rolpa glacier in the Nepalese Third Pole cost $US 3 million in 2002. The authors contended that in many cases in the future, the only adaptation that will be viable is the relocation of communities. Parveen et al. (2015) identified this approach in connection with the communities of Northern Borith and Ghulkin in northern Pakistan, both of which were forced to migrate to higher ground to avoid the risk of flooding. Anacona et al. (2018) discussed how the management of glacial hazards and climate change can be held back by Glacier Protection Laws (GPLs), which have been established to ensure protection from damaging mining operations in countries including Argentina and Chile. The authors found that the dynamics of climate change were not factored into the GPLs, meaning that necessary actions to adapt to emerging hazards, for example, the draining of glacial lakes to prevent a dangerous outburst flood risk, might not have been given sufficient recognition within the planning system.

Strategies for adapting intangible cultural ES to the risks of climate change, especially ones relating to socio-cultural values, are given much less prominence in the academic literature. However, the study of Sherry & Curtis (2017) conducted ethnographic observations and interviews with 53 members of a rural Sherpa community in Nepal, a location greatly threatened by the possibility of a glacial outburst flood. The authors found that their interpretations of risk were largely based on science and religious beliefs were central to coping. Moreover, spiritual practices, such as rituals and prayer, were considered to enhance social cohesion, aiding coping mechanisms. According to the authors, socio-cultural factors should be integrated into glacial risk reduction strategies. However, there is evidence that the integration of values into strategic planning is insufficient to adapt to extreme glacier-related risks to life and community. Shijin & Dahe (2015) discussed how 65% of indigenous residents living on the Tibetan Plateau near to the Mount Yulong Snow have recognised a need to migrate to adapt to climate change, despite considering the area to be their spiritual home. Steinberg (2008) painted an even bleaker portrayal in relation to indigenous peoples in Peru, who experience the loss of glacier ice and snow from mountain peaks as a sign of the departure of their gods and the end of the world.

5.3 Limitations of the model

This study used the integrated ES cascade and co-production model of Malinauskaite et al. (2021b) to identify steps in the formation of ES specific to glaciers. Although a useful analytical device, several scholars have raised concerns about human well-being conceptualisations involving the ES lens. Seven of these are summarised below together with the mitigation efforts of the authors:

- Inconsistent use of terminology – La Notte et al. (2017) contended that practitioners often use the same terms but with different assumptions concerning definition. In this paper, the authors endeavoured to address this issue through clearly articulated definitions of co-production processes in Section 2.
- Simplification of linkages – the co-production stages linking ecosystem functions and processes to the receipt of human well-being involve an inevitable simplification of complexity (Norgaard, 2010). This is accurate with respect to this study but is of limited consequence to a thematic rather than an in-depth, location-specific analysis.
- Deeper social issues are overlooked or given insufficient attention – factors such as socio-economic complexities, governance systems and power relations are all relevant in the context of co-produced ES (Malinauskaite et al., 2021a). These need to be studied further with respect to glacier ES in location-specific contexts.
- Overemphasis on commercialisation – the model perhaps suggests too much importance should be placed on exchange values in markets (Cook et al., 2020), however, the socio-cultural dimension is included and this paper has emphasised the role this value domain plays in human well-being associated with several glacier ES. Greater emphasis could be placed in the model on the role of non-market valuation techniques for estimating marginal changes in the economic value of ES.
- Uncertainty concerning what constitutes a final or intermediate ES (Haines-Young and Potschin, 2018). In this paper, glacier meltwater was considered to provide a role as both an intermediate and final ES – intermediate as an input to agricultural production, final in the form of freshwater for drinking and hydropower. This approach may mean

that the former benefits are underrepresented by the model and they are known to be of immense significance to a population broaching 2 billion (IPCC, 2019).

- Overlapping ES and bundles – as is common to cultural ES (Clements & Cumming, 2017), many of the ES in this paper occur in the form of bundles rather than the individualised aspects of well-being they were depicted as, for example, aesthetics and recreation, and aesthetics and artistic inspiration. The approach in this paper was a simplification of complexity for the purposes of illustrating the many, diverse ways in which glacier ES provide human well-being benefits.
- Relatively few valuation studies to evaluate benefits – there is a general shortage of ES valuation studies, both economic and socio-cultural, in cryospheric landscapes, such as the Arctic, compared to other parts of the world, and there have been calls in the literature for more research in this regard (Malinauskaite et al., 2019). Some studies constitute exceptions to this generalisation, such as the work of Euskirchen et al. (2013), which focused on the regional monetary losses likely due to lost climate regulation services associated with cryospheric thawing in the Arctic.

5 Conclusion

This paper provided the first classification of glacier ES in the academic literature, applying the widely used CICES typology for this purpose. The examples highlighted in this paper illustrated how co-production processes are necessary for many glacier ES to be mobilised, appropriated and commercialised, especially provisioning ES which are of critical importance to the lives and livelihoods of innumerable communities around the world. Furthermore, the co-production lens in this paper provided a very useful means of understanding the formation of glacier ES and the intricacies of climate change impacts, facilitating understanding of how the costs and benefits of glacier ES are altering. Glacier retreat disrupts the biosphere and vital supply-side contributions derived from glacier ecosystem functions and processes. The downstream implications may be severe, especially for people and economies in the Third Pole and tropical Andes, who are reliant on glacial meltwater for agricultural production and hydropower, especially during annual dry seasons.

In terms of co-production, ESP is changing, and climate change impacts drive the exploration of new economic benefits and cause new costs that must be incurred in order to deliver the same level of ES benefits. Some commercial benefits may enlarge in the short to medium term, then diminish rapidly thereafter as the full impacts of glacial retreat are experienced. Many of the costs to human well-being, both monetary and socio-cultural, are likely to be of such severity that climate change mitigation measures are insufficient, requiring adaptive management interventions. These too constitute co-production measures, human efforts in local contexts to protect the biophysical structures that enable and sustain the ES flow, and should therefore be inclusive and not solely top-down interventions carried out without understanding the values and needs of those impacted by the adaptation.

Some glacier ES impacts may be too extreme to be adapted to, presenting risks to the survivability and underlying culture of communities, indigenous and non-indigenous alike. For indigenous peoples, the ongoing retreat of glaciers may constitute a significant cultural loss, given the close bonds and associations they hold with these beacons of power and the sacred.

A co-production perspective has been central to identifying some core requirements in the adaptive management of glacier ES. These are outlined as follows:

1) Ensuring demand and supply management of provisioning ES, both hydropower and freshwater for drinking and irrigation purposes. This may involve the mapping and identification of new reservoirs for water storage, including newly emerging glacial lakes.
2) Careful design of hydropower plants that is considerate of the likely impacts of climate change over the course of the next century. This should be conducted with respect to the selection and sizing of turbines and reservoir design that minimises the overspill likelihood.
3) Enhanced disaster preparedness through comprehensive risk management and planning. This will involve the contribution of research institutes in identifying and quantifying climate change-related risks of glacier melting and retreat, in addition to roles for the private and public sector in building adequate capacity to minimise the potential for disastrous events such as glacier outburst floods.
4) Greater commitment to mitigation through national and international collaboration on policies and technologies for reducing greenhouse gas emissions, as well as specific knowledge sharing on the monitoring and management of risks relating to glacier change.

With regards to ecosystem services practitioners, there is a deeper but no less significant role that can be played. Greater understanding of the benefits and values underpinning glacier ES around the world, and knowledge building concerning the economic and socio-cultural impacts of the loss of glacier ES would facilitate both academic advancement and provide a useful practical contribution to informing decision-making. In addition, there is an evident need for more know-how concerning how the values people hold for glacier ES are often socially constructed rather than formed on a solely individual basis, with analysis of how these might be influenced by power inequalities and different governance systems.

Acknowledgements

This paper has been funded by NordForsk (grant number 76654) via their financial support to the Nordic Centre of Excellence ARCPATH (Arctic Climate Predictions – Pathways to Resilient, Sustainable Communities).

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