Glaciers and postglacial ecosystems: common goods to protect in the Anthropocene

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Abstract

Glacier shrinking and the development of postglacial ecosystems related to anthropogenic climate change is one of the fastest ongoing ecosystem shifts, with paramount ecological and societal cascading consequences globally (Huss et al., 2017; Milner et al., 2017; Cauvy and Dangles, 2019; IPCC, 2021). Yet, no complete spatial analysis exists to quantify or anticipate this major changeover (Ficetola et al., 2021; Zimmer et al., 2022). Here we model glacier responses to climate projections until 2100 and subglacial terrain to explore the ecological trajectory of all glaciated areas, outside the Antarctica and Greenland ice sheets. Depending on climate change magnitude, glaciers could lose less than one quarter to half of their area by 2100. Mainly composed of terrestrial, then marine and freshwater areas, deglaciated areas could range from the equivalent surface of Nepal to Finland. Ecological conditions in deglaciated areas will remain extreme in some regions, offering refuges for cold-adapted species, but become mild in others, favouring biogeochemical processes, primary productivity and generalist species. This unprecedented travel into the future of cold regions shows that glaciers and postglacial ecosystems have key roles to play to face climate change, biodiversity loss and freshwater scarcity. Less than a third of these vulnerable common goods, barely considered in nature conservation policies (IPBES, 2019), are located within protected areas. We therefore call to urgently enhance both climate change mitigation and the in-situ protection of these key ecosystems to secure their existence, functioning and values.

Main Text

A giant ecosystem shift to explore (409w without refs)

What keeps life going? Biologically, one could state that to ensure their future, organisms reproduce and try to spread out. But each species has an environmental niche, restrained by frontiers (Mayor et al., 2017; Cauvy-Fraunié and Dangles, 2019; Xu et al., 2020). Although the >200’000 Earth’s glaciers and two continental ice sheets host species adapted to thrive in their extreme environments (Hotaling et al., 2017; Stibal et al., 2020; Gobbi et al., 2021), they are perfect examples of such a frontier. Indeed, the 10% of lands and the part of oceans covered by these flowing ice masses are uninhabitable for most life forms. Yet, in the Anthropocene where humans have become the main force of planetary changes and especially because of anthropogenic climate change (Folke et al., 2021; Pötner et al., 2021), glaciers are melting at an accelerating pace (IPCC 2019 & 2021; Hugonnet et al., 2021; Roe et al., 2021; Slater et al., 2021). This results in a gigantic ecosystem shift globally, modifying living conditions for cold-adapted and *generalist* species (Huss et al., 2017; Milner et al., 2017; Cauvy and Dangles, 2019). Terrestrial, freshwater and marine ecosystems such as forests, lakes or fjords are hence developing in the 10^5 km^2 abandoned by glaciers since the Little Ice Age - Industrial era transition, around 1900 (Shugar et al., 2020; Ficetola et al., 2021; Pittman et al., 2021). In addition, the progressive extinction of these icy giants can have local to global cascading consequences. Ice melt impacts hydrological and biogeochemical cycles, sea level, or ocean and climate systems functioning and thereby, the distribution of life conditions and human activities (Huss et al., 2017; Milner et al., 2017; Cauvy-Fraunié and Dangles, 2019; Immerzeel et al. 2020; McKay et al., 2022).

Recognized as key climate indicators and due to their overarching influence on the Earth system, glaciers are thoroughly studied. Major improvements were recently made to quantify and anticipate their volume variations in response to climate change, and the consequences on sea level and freshwater cycle (Huss & Hock, 2018; Hock et al., 2019; IPCC, 2019; Edwards et al., 2021; Hugonnet et al., 2021; Malles et al., 2021). To date however, beyond studies focusing on specific ecosystems or regions (*e.g.* Shugar et al., 2020; Lee et al., 2021; Linsbauer et al., 2021; Pitman et al., 2021), no detailed global-scale, quantitative and systemic analysis exists regarding glacier retreat and the ecology of emerging deglaciated areas (Zimmer et al., 2022). Using the Global Glacier Evolution Model (GloGEM; Huss & Hock, 2015), we explore here, for the first time to our knowledge, the 21st century ecological trajectory of the ~650'000 km^2 - corresponding to the area of Afghanistan or France - currently covered by Earth's glaciers outside the Greenland and Antarctica ice sheets. In addition to glacier responses to climate projections, we provide first-order estimates of the size, topography and air temperature of future deglaciated areas to anticipate the development of postglacial ecosystems. In other words, we propose the first virtual expedition in a new ecological frontier, related to climate change. While glaciers and postglacial ecosystems remain largely unconsidered in nature conservation agendas (Anacona et al., 2018; Bosson et al., 2019; Zimmer et al., 2022), our journey within these vulnerable pristine areas will question their role to face some of the most pressing issues of the Anthropocene: climate change, habitat degradation, biodiversity loss and freshwater scarcity (Ripple et al., 2017; Immerzeel et al. 2020; Bradshaw et al., 2021; Folke et al., 2021; Pötner et al., 2021; McKay et al., 2022).

Glaciers and deglaciated areas over the 21st century (1497w without ref)

We used global glacier outlines (RGI Consortium, 2017), digital elevation models of the subglacial terrain (Farinotti et al., 2019a) and climatic data (Eyring et al., 2016; Hersbach et al., 2020) to run GloGEM (Huss & Hock, 2015) and quantify the future response of each glacier to climate change, as well as the characteristics of emerging deglaciated areas until 2100. GloGEM has been calibrated by the 2000-2019 volume changes of each glacier (Hugonnet et al., 2021), and provides results at a 25-200 m spatial resolution on a regular grid. In the IPCC's framework (IPCC, 2021), climatic projections were provided by Global Circulation Models (GCMs, Eyring et al., 2016) constrained by five Shared Socio-economic Pathways (SSPs, Meinshausen et al., 2020). SSPs predict greenhouse gas emissions from very low (SSP1-1.9, implying emissions cut to net zero around 2050, restraining future global warming between 1 to 1.8°C above pre-industrial level) to very high (SSP5-8.5, assuming emissions will triple by 2075 and global warming will reach 3.3 to 5.7°C above pre-industrial level by 2100). Subglacial terrain was used to classify future deglaciated areas into three topographical and ecosystem categories (Cauvy-Fraunié and Dangles, 2019): (1) areas and overdeepenings below sea level (*i.e.* ocean or lagoon areas potentially filled or in contact with saltwater), (2) terrestrial overdeepenings (*i.e.* depressions above sea level with areas >0.005 km^2 and depths >3 m to anticipate potential freshwater accumulation in lakes or wetlands), and (3) terrestrial areas (*i.e.* the remaining emerging deglaciated areas). To explore future ecological conditions, we combined resulting terrain slope and overdeepening depth in emerging deglaciated areas with future mean annual air temperature (MAAT). It allowed us to anticipate the development of future *extreme* (steep/deep and cold), *intermediate* (steep/deep or cold), and *mild* (flat/shallow and temperate) habitats where biological processes will be limited or enhanced. We used 30° as a threshold for terrestrial slopes to separate flat from steep terrains, above which rock walls and gravitational processes strongly limit biotic colonisation (Carrivick et al., 2018). A depth of 5 m was used in overdeepenings to separate shallow from deep zones. This threshold is recognized as a functional shift in aquatic ecosystems, especially in relation with energy exchange with atmosphere and photosynthetic activity (Richardson et al., 2022). A MAAT of 0°C served to roughly distinguish cold (polar, subpolar, alpine and tundra) from *temperate* environments. As nutrient accumulation, pedogenesis or species dissemination, and thereby primary succession and ecosystem development can take time after glacier retreat (Cauvy-Fraunié and Dangles, 2019; Ficetola et al., 2021; Khedim et al., 2021), we analysed a stepwise change in *habitats* over the whole 21st century. To explore the role of postglacial ecosystems as emerging carbon sinks and based on reference values in these environments (Egli et al., 2012; Khedim et al., 2021), we computed a first order range of potential carbon sequestration in the soils of emerging terrestrial areas (see methods). We present here, globally and by glacierized region (GTN-G, 2017), the means and standard deviations obtained for each SSP from 4 to 13 individual GCM results. We discuss the results for the two end-member SSPs to explore the full spectrum of potential responses to climate change. Our results have to be interpreted with care due to uncertainties related to the modelling of climate, glacier evolution and subglacial topography (see Methods).

Outside the ice sheets of Antarctica and Greenland, glaciers covered 664,500 ± 6060 km^2 in 2020 (Fig.1A, 2 and Tab.S1). In response to projected climate change and following the acceleration of their decline (Hugonnet et al., 2021, IPCC, 2021), glaciers will largely experience negative mass balances, leading to noticeable losses of their volume, area and number. Although deglaciation is expected to globally occur at a similar rate regardless of the greenhouse gas emissions until the 2030 decade, strongly diverging trajectories appear in the second half of the 21st century (Fig.1A-B). According to GloGEM results, under the high-emission scenario SSP-5-8.5, half of their 2020 area (339,000 ± 99,000 km^2) are expected to vanish by the end of the century when deglaciation will approach 50,000 ± 10,000 km^2/decade. The relative loss will be most marked in Low Latitudes (*i.e*. for tropical glaciers), Central Europe, Caucasus & Middle East, North Asia, Western Canada & USA and South Asia East, where less than 15% of the 2020 glacierized areas are expected to subsist by 2100 (Fig.2, Tab.S1, Fig.S1-3). Conversely, under the low-emission scenario SSP-1-1.9, global deglaciation rate will curb around 10,000 km^2/decade after 2080 and 78 ± 8% of the 2020 glacier surface (517,000 ± 55,000 km^2) would subsist by 2100. In Arctic Canada North, Antarctic & Subantarctic, Greenland periphery, New Zealand, Iceland, Russian Arctic, South Asia West and Southern Andes, relative loss between 2020 and 2100 would be < 25%, and glacier extent might be stabilised in many low to mid-latitude regions by the end of the century (Fig.S1-3).

Glacier shrinking is expected to liberate 149,000 ± 55,000 (the area of Nepal) to 339,000 ± 99,000 km^2 (the area of Finland) until 2100 (Fig.1A and Tab.S1). The largest deglaciated areas will appear in Alaska, Greenland Periphery and Central Asia (Fig.S4). Globally, emerging deglaciated areas are expected to be composed in 2100 by ~78% of terrestrial areas, and respectively ~14% and ~8% of overdeepenings below and above sea level, regardless of the emission scenario (Fig.1A, Tab.S1). In 10 regions on 19, terrestrial areas will represent more than 90% of the deglaciated area. The retreat of tide-water glaciers would liberate vast overdeepenings below sea level in the Antarctic & Subantarctic (≥ 7,600 ± 1,700 km^2 and 66 ± 28 % of the deglaciated surface in 2100; Tab.S1 & Fig.S6), Russian Arctic (≥ 5,500 ± 3,600 km^2 and 39 ± 11 % respectively) and Svalbard (≥ 3,100 ± 1,800 km^2 and 26 ± 6 % respectively). Cumulated terrestrial overdeepenings areas are expected to be large by 2100 in Alaska (≥ 2,230 ± 1150 km^2; Tab.S1 & Fig. S7), Greenland Periphery (≥ 1,940 ± 2,140 km^2) and Arctic Canada South (≥ 1,260 ± 470 km^2), and represent a significant fraction of the deglaciated areas in Iceland (≥ 18 ± 6 %) and Scandinavia (≥ 13 ± 3 %).

The median slope of emerging terrestrial areas will be 21.5° globally under all emission scenarios (Fig.1C, Tab.S2; Fig.S8-10). This value will be above 25° in high-mountain regions and below 15° in Iceland, Russian Arctic and Antarctic & Subantarctic. Globally, ~70% of emerging terrestrial areas in 2100 (*i.e.* 80,550 ± 31,000 to 188,550 ± 58,000 km^2 depending on the emission scenario) will have slopes below 30° according to estimated bedrock topography currently beneath the ice.

The median depth in emerging overdeepenings both below and above sea level is expected to be around 70 m in 2100 regardless of the emission scenario (Fig.1D; Tab.S2; Fig.S11-S12). Less than 9% of their areas will have a depth smaller than 5 m, representing 2,570 ± 1,030 to 6,050 ± 2,000 km^2. In Arctic Canada North, Svalbard, Russian Arctic and Antarctic & Subantarctic where numerous glaciers reach the ocean, overdeepenings will emerge with a depth of hundreds of metres. Conversely, the median depth will be below 25 m in most regions with land-terminating glaciers.

Depending on climate change magnitude, terrestrial areas are expected to either largely emerge under cold conditions in the low-emission scenario (> 80% of the 2100 area will have negative MAAT, with a median of -5,75°C; Fig.1E, Tab.S2), or under milder conditions in the high-emission scenario (with respective values > 55% and -0,25°C). Due to their formation in the thalweg of deglaciated areas, the situation will be similar but warmer for overdeepenings: ~75% of the 2100 their surface will have negative MAAT (median: -3,75°C, Fig.1F, Tab.S2) under the low-emission scenario. Respective values will be ~35% and +2,25°C for the high-emission scenario. In Arctic Canada North and South, Greenland Periphery, North Asia, Central Asia, South Asia West and East, emerging deglaciated areas are expected to be largely subject to negative MAAT, regardless of the emission scenario (Fig.S13-S18). Conversely, MAAT will be mostly positive in Iceland, Low Latitudes, Southern Andes and New Zealand, whereas the situation will depend on emission scenarios in the other regions.

Among the 210,000 glaciers, 148,100 ± 28,500 (71 ± 14 %) to 33,900 ± 24,000 (16 ± 11 %) are expected to subsist by 2100 according to emission scenarios (Tab.S1; Fig.S19-20). In deglaciated areas, the number of emerging overdeepenings is expected to range from 79,800 ± 29,500 to 185,100 ± 44,500 in 2100 (Tab.S1; Fig.S20-21). Their numbers will be especially large (≥ 8,000 in 2100) in Greenland Periphery, Alaska and Central Asia.

Glaciers are expected to store 106,640 ± 9810 to 72,650 ± 22,490 km^3 of water in 2100 (respectively 79 ± 7 to 54 ± 17 % of the 2020 volume; Fig.1G; Tab.S1; Fig.S22-23). The highest absolute loss would occur in Alaska, Antarctic & Subantarctic and Russian Arctic (≥ 3,800 km^3) while "small" glaciers of Low Latitudes, South Asia East, North Asia, Central Europe and Western Canada & USA would lose in any case more than 55% of their 2020 volume. Under the high-emission scenario, less than 5% of the 2020 volume is expected to remain by 2100 in Low Latitudes, Central Europe and Caucasus & Middle East. Emerging overdeepenings might store 3,940 ± 690 to 8,960 ± 2040 km^3 of water in 2100, corresponding to 3 ± 1 to 7 ± 2% of the 2020 or 4 ± 1 to 12 ± 3% of the 2100 glacier water-equivalent volume (Fig.1H; Tab.S1; Fig.S23-25).

Key ecosystems in a decisive period (998w without refs)

Although computing a slightly larger area loss, our results are in line with the latest modelling of global glacier evolution (Hock et al., 2019; Marzeion et al., 2020; Rounce et al., in press). They underline the importance of short-term greenhouse gas emissions on the intertwined destiny of glaciers and the Earth system (Fig.1 & 2; IPCC, 2021; Rounce et al., in press). Triggering positive feedback, uncontrolled emissions will lead to a major climate change that would durably lock the planet into a hot system where glaciers would go extinct (Steffen et al., 2018; McKay et al., 2022). Conversely, rapid and far-reaching emission cuts can stabilise global surface temperature after 2040 (IPCC, 2021), allowing the preservation of large glaciers (Fig.1 & 2). Although less than the continental ice sheets, the 210,000 glaciers have an impact on Earth climate, through their influence on albedo, energy or water fluxes. Depending on climate change magnitude, the evolution of glaciers and ice sheets will thus also act either as a negative or positive feedback that will limit or enhance climate change. The preservation of ice masses is hence both a consequence and an imperative of climate change mitigation whereas their decline will make the latter hardly achievable. In addition, the large emerging deglaciated areas will also influence climate evolution. Decreasing surface albedo and potentially releasing greenhouse gases, deglaciation might foster climate change (Pötner et al., 2021; Pi et al., 2022; Wu et al., 2022). Conversely, carbon capture and storage in postglacial ecosystems through growing biogeochemical processes (e.g. pedogenesis, peat formation, underwater weathering or sediment accumulation) and biomass (e.g. trees, planktons, seabed communities) will contribute to mitigate climate change (Peck et al., 2010; St-Pierre et al., 2019; Khedim et al., 2021; Cui et al., 2022; Rumpf et al., 2022). As a first order estimation, we computed that the soils of all emerging terrestrial areas could sequester 15 to 270 Mt of carbon over the 21st century according to emission scenarios (see methods; Tab.S4 & Fig.S26). It corresponds to the carbon stored in the surface biomass of 300 to 17,000 km^2 of lowland tropical rainforest (Peck et al., 2010), and illustrates the unconsidered but increasing role of postglacial ecosystems as carbon sinks (Pötner et al., 2021).

Storing 135,000 km^3 of water in 2020 (Fig.1G), and releasing freshwater during melt seasons that locally can coincide with dry periods, glaciers are a major element of the hydrological cycle. Preserving the maximum possible glaciers and ice sheets through climate change mitigation will hence secure water supply in many regions, ocean level that have strongly shaped life evolution and distribution in recent

Earth history (Huss et al., 2017; Milner et al., 2017; Huss et Hock, 2018; Steffen et al., 2018; Immerzeel et al. 2020; IPCC, 2021; Pötner et al., 2021). While glaciers melt and evapotranspiration intensify, emerging postglacial ecosystems are becoming increasingly important components of the freshwater cycle. New lakes, wetlands, rivers, but also terrestrial biomass and soils locally store, purify, regulate and provide blue and green water (Shugar et al. 2020; Keestra et al. 2021; Pitman et al. 2021; Wang-Erlandsson et al., 2022). However, in comparison to existing glaciers, postglacial ecosystems will store a limited amount of water. For instance, we model that emerging terrestrial overdeepenings in low to mid-latitude regions by 2100 could retain 0.4 to 5% of glacial meltwater between 2020 and 2100 (Tab.S1, Fig.S23 & 25), a range including the ~1% computed for meltwater storage in emerging glacial lakes over the two last decades globally (Shugar et al. 2020). Overall, when considering all emerging overdeepenings, including the large and deep ones below sea level that would appear in some polar regions (Fig.S6 & 11), this storage capacity could reach 10 to 15% of glacial meltwater in the course of the 21st century (Tab.S1), contributing hence to somewhat reduce the magnitude of sea-level rise relative to total ice loss (Huss & Hock, 2015). Modifying water and mater fluxes, emerging overdeepings will also influence water-related hazards. While some new glacial lakes will produce catastrophic outburst floods, most of them will act as sediment sinks that buffer upstream hazards (Carrivick & Tweed, 2013; Shugar et al. 2020). In regions where glaciers initially reached the ocean, the development of postglacial shoreline ecosystems will provide protection from sea-level rise and storm surges (Pötner et al., 2021).

Because glaciers host various specialised species, influence downstream hydrosystems and more broadly climate and water cycle, their decline will impact geodiversity, biodiversity and many ecosystems globally (Huss et al., 2017; Milner et al., 2017; Cauvy-Fraunié and Dangles, 2019; Stibal et al., 2020; Gobbi et al., 2021; Bollati et al., 2022). Preserving glaciers by mitigating climate change will thus limit the loss of this unique habitat and related biodiversity (*e.g.Andiperla willinki* Aubert, 1956; *Sinenchytraeus glacialis* Liang, 1979*),* glacier-influenced systems and related biodiversity (*Diamesa steinboecki* Goetghebuer, 1933*, Cassidulina reniforme* Nørvang, 1945*, Nebria Germari* Heer, 1837; Cauvy-Fraunié and Dangles, 2019), and important ecological changes at broader scale. Our characterisation of retreating glaciers and emerging deglaciated areas allows to develop a novel systemic view on the glacial and postglacial evolution (Fig.1-3). Diverse ecosystems among which rock outcrops, sediment accumulations, grasslands, shrublands, forests, rivers and floodplains, lakes, wetlands, lagoons, rocky and sedimentary shores, sea beds or open ocean can supersede glaciers (Fig.4A). While ecosystems are worldwide largely degraded (especially in freshwater and coastal environments; Watson et al., 2019; Albert et al., 2020; Bradshaw et al., 2021; Pitman et al., 2021; Pötner et al., 2021), postglacial ecosystems represent rare growing pristine marine, freshwater and terrestrial areas. Under the low-emission scenario, *extreme* to *intermediate* ecological conditions are expected to dominate deglaciated areas globally until 2100, and in Arctic Canada North & South, Greenland Periphery, North & Central Asia and South Asia East & West under all emission scenarios (Fig.3; Tab.S3; Fig.S27-29). This emphasises how, in parallel to the large remaining glaciers for specialised species, postglacial ecosystems where primary successions occur under low initial nutrient availability (Ficetola et al., 2021), will offer new habitats and refuges for the particularly vulnerable cold-dependent and/or oligotrophic species (e.g., *Lednia tumana*, Muhlfeld et al., 2020; Pacific Salmons, Pitman et al., 2021). In contrast, postglacial ecosystems of Iceland, Low Latitudes, New Zealand and Southern Andes will mostly emerge under *mild* to *intermediate* conditions, limiting the survival of cryophilous and potentially endemic, species (e.g., *Deleatidium cornutum* Towns & Peters, 1996;Winterbourn et al. 2008), or of aquatic or hygrophilous species as observed in the tropics with the decrease of cold water supply (e.g. *Paratrechus boussingaulti* Mateu & Moret, 2001;Rosero et al. 2021). Here and in numerous regions under the high-emission scenario, these conditions are expected to boost biogeochemical processes, primary productivity and the colonisation by *generalist* species from downstream areas, often characterised by higher anthropogenic pressures (Cauvy-Fraunié and Dangles, 2019). In the wettest low to mid-latitude regions where glaciers sometimes flow below treelines (e.g., in areas of Rocky Mountains, New Zealand or European Alps; Sigdel et al., 2020; Ficetola et al., 2021),primary forests may rapidly develop in the 10^3 to 10^4 km^2 of emerging lands under *mild* conditions (Fig.3), and locally counterbalance forest loss related to deforestation or climate change (Curtis et al., 2018; Pötner et al., 2021; Senf et al., 2021; Anderegg et al., 2022). Overall, while the loss of glaciers and related ecosystems will dramatically contract the distribution of adapted species (Cauvy-Fraunié and Dangles, 2019; Stibal et al., 2020; Gobbi et al., 2021; Rosero et al. 2021), the development of various postglacial ecosystems at different stage of evolution and under diversified topo-climatological conditions may locally enhance ecological connectivity, adaptation capacity and resilience for *generalist* species (Shugar et al., 2017; Pitman et al., 2021; Pötner et al., 2021).

Common goods to protect (1235w without refs)

Glaciers and, in default, emerging postglacial ecosystems have a crucial - and partly unrecognized and unquantified - role to play whilst climate change, nature decline and freshwater scarcity intensify (Bosson et al., 2019; IPBES, 2019; IPCC, 2021; Pötner et al., 2021). The functional importance of these wilderness areas will even grow as global artificialization increases and most of ecosystems are pushed beyond their resilience capacities (Ripple et al., 2017; Watson et al., 2019; Bradshaw et al., 2021; Folke et al., 2021; McKay et al., 2022). Interestingly, almost all glaciers and emerging postglacial ecosystems are located on public lands, owned by local communities (Anacona et al., 2018; Zimmer et al., 2022). They are hence mostly *common goods*, governed by public authorities. Unfortunately, in addition to climate change, pollutions or alien species (Kang et al., 2020; Pötner et al., 2021), mining, tourism, hydropower production, forestry, agri/aquaculture, fishing, hunting or geohazards mitigation can locally affect them (Haeberli et al., 2016; Anacona et al., 2018; Farinotti et al., 2019b; Shugar et al., 2020; Pitman et al., 2021; Zimmer et al., 2022). Indeed, they are largely considered as a source of economic opportunities or geohazards to mitigate in the dominant anthropocentric perspective (IPBES, 2022; Fig.4B). Activities and infrastructures hence multiply on these vulnerable ecosystems, sometimes privatising their areas or resources, as a result of local, short-term or sectorial anthropocentric visions where their critical bio-ecocentric roles are poorly considered and sometimes totally ignored (Fig.4B). In parallel, especially because the interconnexion between changing cryosphere and biosphere remains barely recognised, glaciers and postglacial ecosystems receive limited attention in nature conservation policies (Anacona et al., 2018; Bosson et al., 2019; Diaz et al., 2019; Watson et al., 2019; Dinerstein et al., 2020; Maxwell et al., 2020). Therefore, to secure their values and functions for the general interest, it is thus urgent to limit the increasing unsustainable uses and irreversible damages (Zimmer et al., 2022) by developing an integrative view to better know, consider and protect these common goods. We propose some basis for such an integrative and stewardship framework (Fig.4B&C). From global to local scale, two complementary actions have to be rapidly intensified to preserve these ecosystems.

Firstly, to guarantee their existence (especially limit glacier decline) and functioning, we echo the scientists' warnings to urgently transform human activities to curb climate change, biodiversity loss and freshwater scarcity (Fig.4C: A1; Steffen et al., 2018; Ripple et al., 2019; Dinerstein et al., 2020; Immerzeel et al. 2020; Folke et al., 2021; Pötner et al., 2021). If tackling global changes is an unprecedented challenge for humanity, glaciers and postglacial ecosystems have great potential to raise awareness and leverage collective reactions (Bosson et al., 2019). For instance, whilst Switzerland does not yet respect its Nationally Determined Contribution to the Paris Agreement (Roelfsema et al., 2020), a citizen initiative successfully used glacier protection in 2022 to modify national laws and boost climate actions (Hausammann & Reich, 2022). UNESCO and IUCN also used World Heritage glaciers to stimulate global action in the opening of the 2022 United Nations Climate Change Conference (COP27; UNESCO & IUCN, 2022).

Secondly, while respecting the rights of local communities and the imperatives of geohazards mitigation, there is a great opportunity to preserve glaciers and postglacial ecosystems, through the rapid *in-situ* protection of areas delimited by the current (or even Little Ice Age) glacier outlines (Fig.4C: A2). We found that solely 30% of current glacier areas are located within protected areas globally, including respectively 8% and 9% in UNESCO's natural World Heritage (Bosson et al., 2019) and Man and Biosphere sites, and 0,1% in Ramsar sites (Fig.2, Tab.S5; Fig.S30). It illustrates the potential to extend and create well-connected, efficiently and equitably managed protected areas (Diaz et al., 2019; Dinerstein et al., 2020; Pötner et al., 2021) over glaciers and freshly deglaciated areas, and especially in Antarctica periphery, High Mountain Asia or Arctic Canada North, where the percentage of glacier areas protected is very low. *In-situ* protection has no or very limited effect on glacier loss but it can avoid their destruction in mines or ski resorts. Moreover, it contributes to address other local threats and hence, to strongly proactively protect these ecosystems regardless of their glacial or postglacial fates. This idea to secure the *free* ecological evolution of the glaciers on the top of Europe and recently deglaciated areas convinced the French State to create the Mont Blanc Natural Habitat Protected Area over 32 km^2 in 2020 (Bosson et al., 2020). In parallel, the development of environmental or glacier protection laws that recently emerged in some countries (e.g. in Argentina or Chile), and especially their extension on postglacial ecosystems, can also increase their local, national or continental protection and recognition (Anacona et al., 2018; Zimmer et al., 2022). In line with the 1959 Antarctic Treaty System, an International Treaty could even strongly frame human activities, guarantee peace and interest of mankind and nature in all glaciers and emerging postglacial ecosystems. Finally, limiting damaging activities by calling to public "no-go commitments" as in the World Heritage sites (Dudley et al., 2015), or by developing ecosystem's rights (Boyd, 2017), could be other avenues to explore. Increasing *in-situ* nature protection is a gigantic task when global changes exacerbate social and economic tensions (Diaz et al., 2019; Dinerstein et al., 2020; Maxwell et al., 2020; Folke et al., 2021; Zimmer et al., 2022). However, because of their key functions, iconic importance, extent on public lands, limited current human activities at their surfaces and because most of future deglaciated areas have never been available for humankind, protecting glaciers and postglacial ecosystems appears as a relatively *easy*, low-costs – high-benefits action with countless environmental and societal impacts. Constituting a *nature-based solution* of planetary scale (Cohen-Shacham et al., 2016), this action completes initiatives on other pristine areas (e.g. Hogg et al., 2020) and fits with the current calls to urgently implement proactive, multi-benefits and nexus approaches in nature conservation to increase ecosystems and societies adaptation capacity to global changes (Diaz et al., 2019; Dinerstein et al., 2020; Folke et al., 2021; Pötner et al., 2021; IPCC, 2022).

If addressing climate and environmental issues are of utmost priority, one should not be dogmatic and sustainable activities should be authorised in some of these ecosystems (Farinotti et al., 2019b; Zimmer et al., 2022). Within the integrative approach exposed here, we recommend to limit such activities to those that maintain overall nature's values and functioning, hinder, compensate and restore all potential damages while generating transparent benefits for local communities and the general interest through an inclusive process (Fig.4C: A3). However, new infrastructures in the latest wilderness areas must be limited to the strict necessary as it rapidly catalyses cumulative threats (Johnson et al., 2017; Watson et al., 2019). We are unfortunately not living in a benign period in Earth, life and Humankind history as the conditions and the web of life are now deeply altered globally (Ripple et al., 2017; Steffen et al., 2018; Bradshaw et al., 2021; Folke et al., 2021; Pötner et al., 2021; Kemp et al., 2022). In its 250,000 year-long history, *Homo sapiens* has never lived without healthy ecosystems, including glaciers.

Our journey into the future of cold regions shows that deglaciation over the 21st century is expected to occur over 181,000 ± 55,000 to 372,000 ± 99,000 km^2 outside the Greenland and Antarctic ice sheets (Fig.3) and may reach unprecedented levels in recent Earth's history (Steffen et al., 2018; IPCC, 2021). Respectively retracting and expanding the ecological niche of *specialist* and *generalist* species (including humans) in areas that have locally never been recently ice-free, glacier retreat will have paramount cascading ecological and societal consequences globally. This changeover constitutes one of the largest and fastest ongoing ecosystems shifts along with the effects of artificialization, deforestation, desertification or long-term droughts (Pekel et al., 2016; Curtis et al., 2018; Diaz et al., 2019; Shukla et al., 2019). Emphasising the key functional roles of glaciers and in default, of emerging postglacial ecosystems to face climate change, biodiversity loss or freshwater scarcity, our results show the utmost interest to enhance both climate change mitigation and the *in-situ* protection of these common goods. The stewardship framework proposed here to secure their existence, functioning and values echoes two recent major international political developments: (1) the vote on 14/12/2022 during the 77th session of the United Nation General Assembly of a resolution that declared 2025 as the *International Year of Glaciers' Preservation*, March 21st as the *International Day of Glaciers' Preservation*, the future establishment of a *UN Trust Fund in support of activities for Glaciers' Preservation,* and the convening of the *2025 International Conference on Glaciers' Preservation* in Dushanbe; (2) the adoption on 19/12/2022 during the COP15 international biodiversity summit of the *Kunming-Montreal Global Biodiversity Framework* that set targets by 2030 to increase the effective protection of ecosystems of high ecological importance and integrity, safeguard genetic diversity and adaptive potential of species, or prevent the spread of invasive alien species (CBD, 2022). As we need to limit our global impact and reinvent our stewardship of the vulnerable living and abiotic components of Earth, protecting glaciers and postglacial ecosystems appears simultaneously as a priority, impactful and inspiring action.

Declarations

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Author contributions

All authors contributed to design the study, which was coordinated by J.B.B.. M.H. provided the data on glacier evolution and subglacial terrain and J.B.B. and F.A. especially analysed them. J.P. and G.C. respectively analysed carbon sequestration potential in emerging terrestrial areas and the distribution of glaciers in protected areas. J.B.B. prepared figures, supplementary files, and wrote the manuscript that was edited by all authors.

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Methods

A. Modelling glacier evolution

Projections of future glacier retreat at the global scale rely on the Global Glacier Evolution Model (GloGEM; Huss and Hock, 2015, 2018, Compagno et al., 2022a). The model describes the main processes determining glacier mass gain or loss (snow accumulation, ice melt, refreezing, frontal ice ablation by calving of marine-terminating glaciers). Surface mass balance components are computed for each glacier individually on 10 m elevation bands by an accumulation and temperature-index melt model at monthly resolution (Hock, 2003), including a parameterization of sub-monthly variability (Huss and Hock, 2015). Refreezing of melt water and rain in snow and firn is inferred from heat conduction. Frontal ablation is calculated using a simple calving model (Oerlemans and Nick, 2005). Subsequently, annual surface elevation change – and thus glacier retreat or advance – is computed based on a mass-conserving parameterization (Huss et al., 2010). The model is forced with gridded monthly temperature and precipitation data from the ERA-5 re-analysis for the past (Hersbach et al., 2020). For the future, results from 56 climate model chains (based on 13 different Global Circulation Models, GCMs) from the sixth phase of the Coupled Climate Model Intercomparison Project are used (CMIP6; Eyring et al., 2016). GCM results are based on five different Shared Socio-economic Pathways (SSPs; Meinshausen et al., 2020) describing future climate forcing due to different greenhouse gas emissions. For all roughly 210,000 glaciers globally, ice extent referring to about the year 2010 is available from the Randolph Glacier Inventory v6.0 (RGI consortium, 2017). Bedrock topography at a spatial resolution between 25 m and 100 m (depending on glacier size and region) is available from a consensus of five different ice thickness models (Farinotti et al., 2019). GloGEM has been calibrated for each glacier individually to glacier-specific observations of ice volume change between 2000 and 2019 (Hugonnet et al., 2021). Projections of future glacier retreat by GloGEM provide changes in glacier mass balance, area, volume and water runoff at annual resolution and for every single glacier worldwide until 2100. Even though the model is discretized into 10 m elevation bands for computational reasons, the final results on area and thickness changes in individual bands are extrapolated to a regular grid of 25 m to 100 m resolution (Steffen et al., 2022, Compagno et al., 2022b), thus providing two-dimensional fields of glacier extent, as well as the deglaciated area at decadal resolution throughout the 21st century.

B. Topography and air temperature in future deglaciated areas

Deglaciated areas investigated in the present study refer to zones covered by glaciers around the year 2010 (RGI consortium, 2017) that are expected to become ice-free in the course of the 21st century, according to our modelling of glacier evolution. Subglacial topography (and hence the one of the emerging deglaciated areas) was inferred from the modelisation of present-day ice thickness at a spatial resolution of between 25 m and 100 m (depending on glacier size and region) from a consensus of five different ice thickness models (Farinotti et al., 2019). These models infer local glacier thickness based on considerations of the principles of ice flow dynamics and are calibrated with a large data set of point observations, mostly from ground-penetrating radar (Welty et al., 2020). According to this *elementary* bedrock topography, future deglaciated areas and hence postglacial ecosystems were categorised into three main types (Cauvy-Fraunié and Dangles, 2019): (1) areas and overdeepenings below sea level (*i.e.* ocean or lagoon areas potentially filled or in contact with saltwater), (2) terrestrial overdeepenings (*i.e.* depressions with areas >0.005 km^2 and depths >3 m above sea level as potential lakes or wetlands), and (3) terrestrial areas (*i.e.* the remaining deglaciated areas). Due to the inherent uncertainties in climate, glacier evolution and ice thickness modelling (see Uncertainties section below), we plainly acknowledge that our results only provide first orders of magnitude of ecosystem evolution, and surface estimates have to be considered with caution. Similar exploratory modelling of postglacial ecosystem emergence at regional scale (e.g Haeberli et al., 2016; Compagno et al., 2022; Lee et al., 2022 for lakes, or Pitman et al., 2022 for rivers) generates large interest in the academic, nature conservation, land planning or policy-making fields. Collecting *in situ* observations and modelling at finest scales to improve the anticipation of the transition between glaciers and the diverse postglacial ecosystems remain an important research challenge that will be the object of numerous research in the near future, as an extension of the *pioneer* global dataset presented here.

During deglaciation, in addition to the emergence of bedrock depressions shaped by glacial erosion, the accumulation of materials can form topographical dams and lead to the formation of postglacial lakes (i.e. moraine-dammed, landslide-dammed, ice-dammed lakes, e.g. Carrivick & Tweed, 2013; Shugar et al., 2020; Compagno et al., 2022) or lagoons separated from the ocean by a sedimentary shoreline (e.g. the iconic Jökulsárlón in Iceland). However, we were not able to model and anticipate the very complex formation of these depressions dammed by materials, and thereby solely considered water accumulation in potential topographic depressions (*overdeepenings*). Sediment fluxes can be very important in a deglaciation context (e.g. Ballantyne, 2002) and thus, the topographic depressions emerging from glacier retreat can be rapidly filled (e.g.Carrivick & Tweed, 2013; Bianchi et al., 2020; Stephen et al., 2022). Nevertheless, as sediment production and fluxes were not considered in our modelling, we were unable to anticipate the potential filling that could occur in emerging ovedeepenings, and solely considered them as potential aquatic ecosystems.

We detected and discriminated overdeepenings below and above sea level by modelling potential water tables in topographic depressions (e.g. Linsbauer et al., 2012). When the emerging overdeepening elevation was below the sea level, we set the potential water level at 0 m of elevation and considered them as future marine or marine-influenced ecosystems. In contrast, the depressions above sea level were classified as terrestrial overdeepenings and associated with potential freshwater ecosystems. Although the uncertainty of the modelled topography is important (see the Uncertainties section), we voluntarily set *small* thresholds in area (>0.005 km^2) and depth (>3 m) in order to detect the majority of the potential future freshwater reservoirs on lands, as lakes or diverse wetland ecosystems such as ponds, marsh, peatlands, floodplains, groundwater in sediment accumulations. Finally, all remaining deglaciated areas above sea level, were considered as terrestrial areas.

The characteristics of the deglaciated areas were analysed at decadal intervals by evaluating surface change and elevation of emerging topography, allowing to compute the slope of terrestrial areas and depth of emerging overdeepenings. The mean annual air temperature (MAAT) in postglacial terrestrial and overdeepenings areas was computed by aggregating monthly air temperatures based on climate re-analysis data (ERA5, 0.5x0.5 degree resolution) and from climate projections for the future (Eyring et al., 2016; Meinshausen et al., 2020) at the annual scale at the elevation of the deglaciated grid cells on lands and at the virtual water table for overdeepenings.

In addition to the analysis of the evolution of the current glacier surface, we also modelled changes of the glacier volume and of the potential water volume in emerging overdeepenings. For comparison with potential water volume in emerging overdeepenings, the glacier volume was converted to water equivalent assuming an ice density of 900 kg m^{-3} (Huss and Hock, 2015). Due to uncertainties in modelled bedrock topography and also the non-consideration of potential sediment or organic matter filling in overdeepenings, the potential water volume in overdeepening below and above sea level is solely provided as a very rough first estimate.

C. *Habitat* analysis

To explore future ecological conditions in emerging deglaciated areas, we combined resulting terrain slope and overdeepening depth with future mean annual air temperature (MAAT). It allowed us to anticipate the development of future *extreme* (steep/deep and cold), *intermediate* (steep/deep or cold), and *mild* (flat/shallow and temperate) habitats where biological processes will be limited or enhanced, and where specialised (e.g. cryophile or oligotrophic species) or generalist species will be favoured (Cauvy-Fraunié and Dangles, 2019).

In this rough classification we used simple thresholds in slope, depth and MAAT to distinguish these four habitat categories in emerging terrestrial areas and overdeepening below and above sea level (Fig.3, Supplementary Fig.S27-29 and Tab.S3). 30° was set as a threshold for terrestrial slopes to separate flat terrains (flood plains and footslopes, where alluvial and fluvial deposits) from steep slopes (unstable moraines, talus, and rockwalls; Carrivick et al., 2018), above which gravitational processes strongly limit biotic colonisation.

A depth of 5 m was used in overdeepenings to separate shallow from deep zones, a threshold recognized as a functional shift in aquatic ecosystems, especially in relation with energy exchange with the atmosphere and with photosynthetic activity (Richardson et al., 2022).

A MAAT of 0°C served to roughly distinguish cold (polar, subpolar, alpine and tundra) from *temperate* environments. If air temperature is an important control of ecosystem and life distribution on lands (e.g. Mayor et al., 2017), its influence on aquatic ecosystems is less straightforward, especially when the water column exceeds several metres and when the presence of turbid glacial meltwaters strongly limits the light and thermal diffusion beyond the subsurface (e.g. Sommaruga, 2015). However, air temperature may noticeably influence aquatic ecosystems functioning and biological processes by, for instance, being an important control of the temperature of the surface water layer or of the occurrence and duration of seasonal ice-coverage (e.g. O'Reilly et al., 2015; Woolway et al., 2020).

D. Carbon sequestration potential in emerging soils

To explore the role of postglacial ecosystems as carbon sinks, we computed a first order range of potential carbon sequestration in the soils of emerging terrestrial areas. The results of this analysis are presented in the Supplementary Tab.S4 and Fig.S26. Carbon accumulation rates in deglaciated soils can vary considerably depending on climate, geomorphological and lithological conditions and tends to decrease with time (Khedim et al., 2021). Despite these variations in accumulation rates, the order of magnitude during the first century after deglaciation can be estimated using soil carbon stock in well-dated chronosequences. Egli et al. (2012) compiled a large data set to estimate these accumulation rates and showed that the order of magnitude minimum, average and maximum are 5, 10 and 50 g $C.m^{-2}.yr^{-1}$ respectively. We used these values to calculate the amounts of organic carbon potentially stored in emerging postglacial soils over the century (by cumulating the amounts stored per year since the date of deglaciation). Three climate projections were used (SSP-1-1.9, 2-4.5, and 5-8.5) for each region (see Tab.S4 and Fig.S26). As pedogenesis velocity depends on surface slope (*stable* soils in gentle terrain vs. *unstable* paraglacial sedimentary slopes and rockwalls, e.g. Ballantyne, 2002) and air temperature (i.e. cold conditions reduce the magnitude of biogeochemical fluxes, e.g. Khedim et al., 2021), we used our *habitat* analysis to differentiate favourable and unfavourable conditions for emerging soils. The rates of 5, 10 and 50 g $C.m^{-2}.yr^{-1}$ were used as minimum, mean and maximum values on favourable surfaces in *mild* emerging habitats (slope < 30° and MAAT > 0°C) and of 1, 5 and 10 g $C.m^{-2}.yr^{-1}$ on *intermediary* and *extreme* emerging habitats (slope > 30° and/or MAAT < 0°C). Given the uncertainties on the accumulation rates, on the nature of emerging terrestrial areas (hard bedrock, moraines or fluvioglacial deposits, etc.) and on the size of the surfaces released over time, we solely presented the extreme limits (15 (min value under SSP-1-1.9) to 270 (max value under SSP-5-8.5) Mt of carbon over the 21st century) of this estimate rather than an average value. This is therefore a fairly rough estimate of the storage potential (which will have to be refined in the future), but it gives an order of magnitude of storage over the century to be compared with anthropogenic emissions (10 Gt of Carbon per year in 2020). To compute an equivalent surface in ecosystems recognised for their carbon sequestration role, we used the reference value of 160 to 435 $t.ha^{-1}$ proposed for aboveground biomasses of lowland American tropical rainforest and used in other cold ecosystems (Peck et al., 2010).

E. Glaciers and protected areas

In order to identify the glaciers in protected areas, we delimited the overlap between worldwide glacier distribution around the year 2010, available from the Randolph Glacier Inventory v6.0 (RGI consortium, 2017), and the protected areas outlines (UNEP-WCMC, IUCN, 2022). The results of this analysis are presented in Fig 2, Supplementary Fig.S30 and Tab.S5 and comprise the number and area of the glaciers located within protected areas recognised by the IUCN's categories I-IV, as well as in the areas listed as UNESCO's Natural World Heritage Sites, under the UNESCO's Man and Biosphere programme, and under the RAMSAR convention on Wetlands of International Importance.

F. Uncertainties

The results presented here are subject to considerable uncertainties. First, our analysis fully relies on the glacier outlines contained in the Randolph Glacier Inventory v6.0 (RGI consortium, 2017). In some regions, glacier outlines are outdated by several decades but the calibration of GloGEM for each glacier individually to glacier-specific observations of ice volume change between 2000 and 2019 (Hugonnet et al., 2021) ensure a realistic update of glacier volume and extent up to the present day. Furthermore, uncertainties in the modelling of future glacier extent arise due to a number of factors related to the forcing data and the glacier model itself (Marzeion et al., 2020). Here we refer to the impact of uncertainties in (1) the climate projections, (2) the data on initial glacier area and ice thickness, and (3) the simplifications and approximations in the glacier model and the calibration procedure. Sensitivity experiments conducted in previous studies (e.g. Huss and Hock, 2015) have indicated that factors (2) and (3) have the potential to importantly influence projected future change of individual glaciers as many physical processes have to be strongly simplified in a global glacier model, and the downscaling of meteorological variables to individual glaciers remains challenging (e.g. Compagno et al., 2021; Rounce et al., in press). With new data sets on ice thickness based on multi-model approaches and validated with comprehensive collections of local observations, the uncertainties of present-day glacier ice thickness, and correspondingly future bedrock topography has been strongly reduced (Farinotti et al., 2019; Welty et al., 2020; Millan et al., 2022). Nevertheless, we note that estimating the volume of potential future bedrock overdeepenings, and thus the depth of new glacial lakes or fjords remains to be highly uncertain as it importantly depends on local patterns of the inferred bedrock (Munoz et al., 2020). Furthermore, future glacial lakes are likely to be partly filled with sediments transported by meltwater but this process is expected to only lead to a loss of 10-25% of overdeepening volume by 2100 at the mountain-range scale (Steffen et al., 2022). Uncertainties in future climate forcing as evidenced by the partly large differences in projected temperature and precipitation changes of the individual global circulation models forced by the same greenhouse gas emission pathways dominate the overall uncertainties of the modelled glacier volume evolution of the 21st century (Marzeion et al., 2020). We thus consider uncertain climate evolution as the main uncertainty source and focus on this factor for estimating the overall uncertainty of glacier evolution in response to each SSP.

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Figures

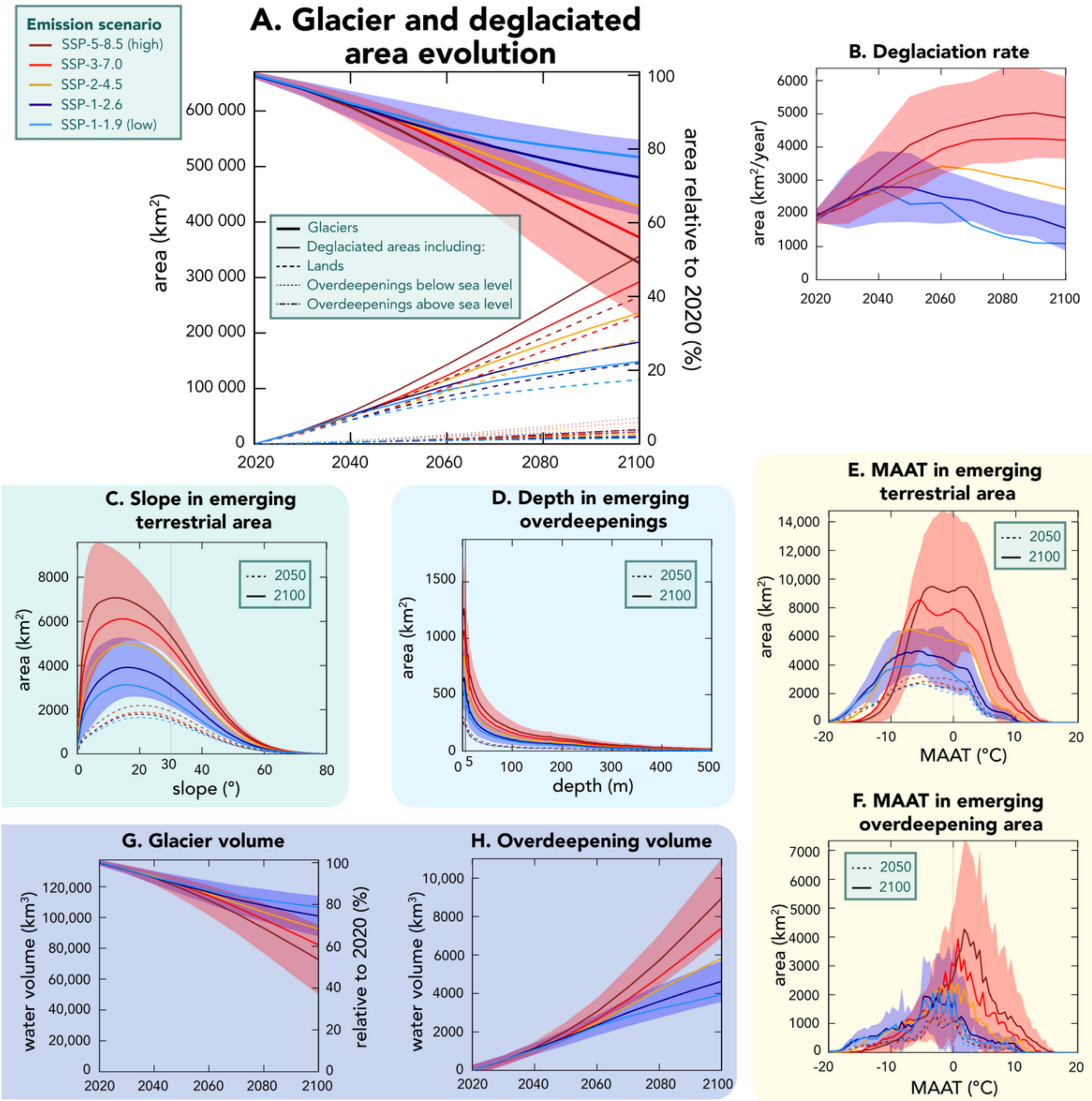

Figure 1

Future evolution of glacier and deglaciated areas (A), deglaciation rate (B), glacier and overdeepenings volume (G, H), slope and depth (C, D), and mean annual air temperature in emerging deglaciated areas (E, F) according to low (SSP-1-1.9) to high (SSP-5-8.5) emission scenarios. Solid and dashed lines correspond to the multi-model means, running all available GCMs by SSPs. For clarity, standard deviations (± 1σ) are solely displayed (coloured beams around the means) for the SSP 1-2.6 in blue (for low-emission scenario as the SSP 1-1.9 has less available GCMs) and the SSP 5-8.5 in red. In (A), the standard deviation for emerging deglaciated areas are not displayed for clarity. Plots D, F and H show results for both overdeepenings below and above sea level. MAAT in emerging deglaciated areas (E, F) were computed as average values over the 2000-2100 period.

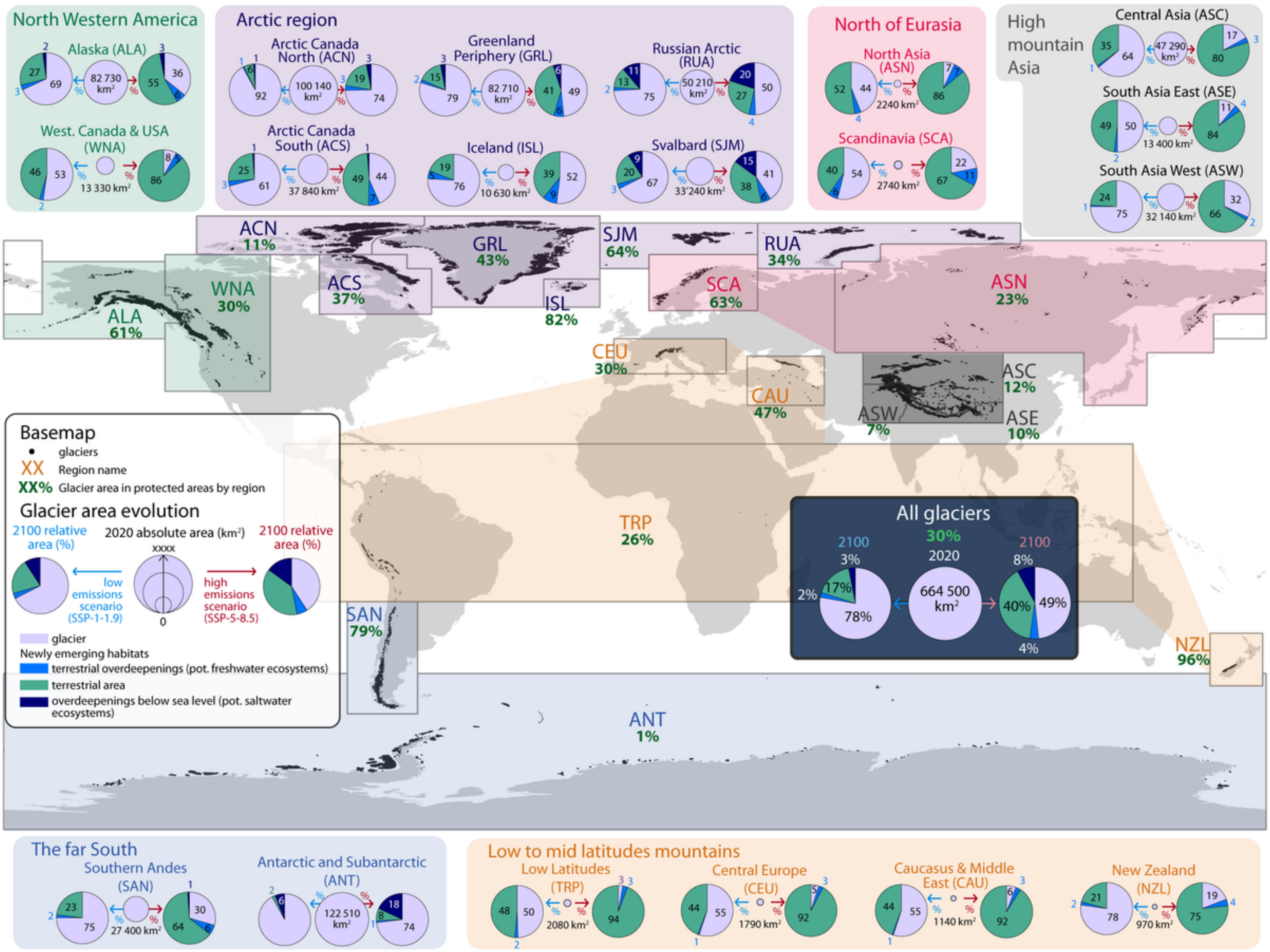

Figure 2

Distribution of glaciers and deglaciated areas from 2020 to 2100. Glacier location and regions originate respectively from RGI Consortium (2017) and GTN-G (2017). We used protected areas outlines (UNEP-WCMC, IUCN, 2022) to compute the ratio of *protected* glacier areas by region (in green). In the boxes, for each region and globally, the central circle refers to the 2020 glacier area. On their left and right, the relative evolution of glacier surface and newly emerging ecosystems is shown for 2100 for the SSP-1-1.9 (low-emission scenario) and 5-8.5 (high-emission scenario), respectively. For clarity, we solely provided mean percentages for 2100 and the associated uncertainties are available in Supplementary Files.

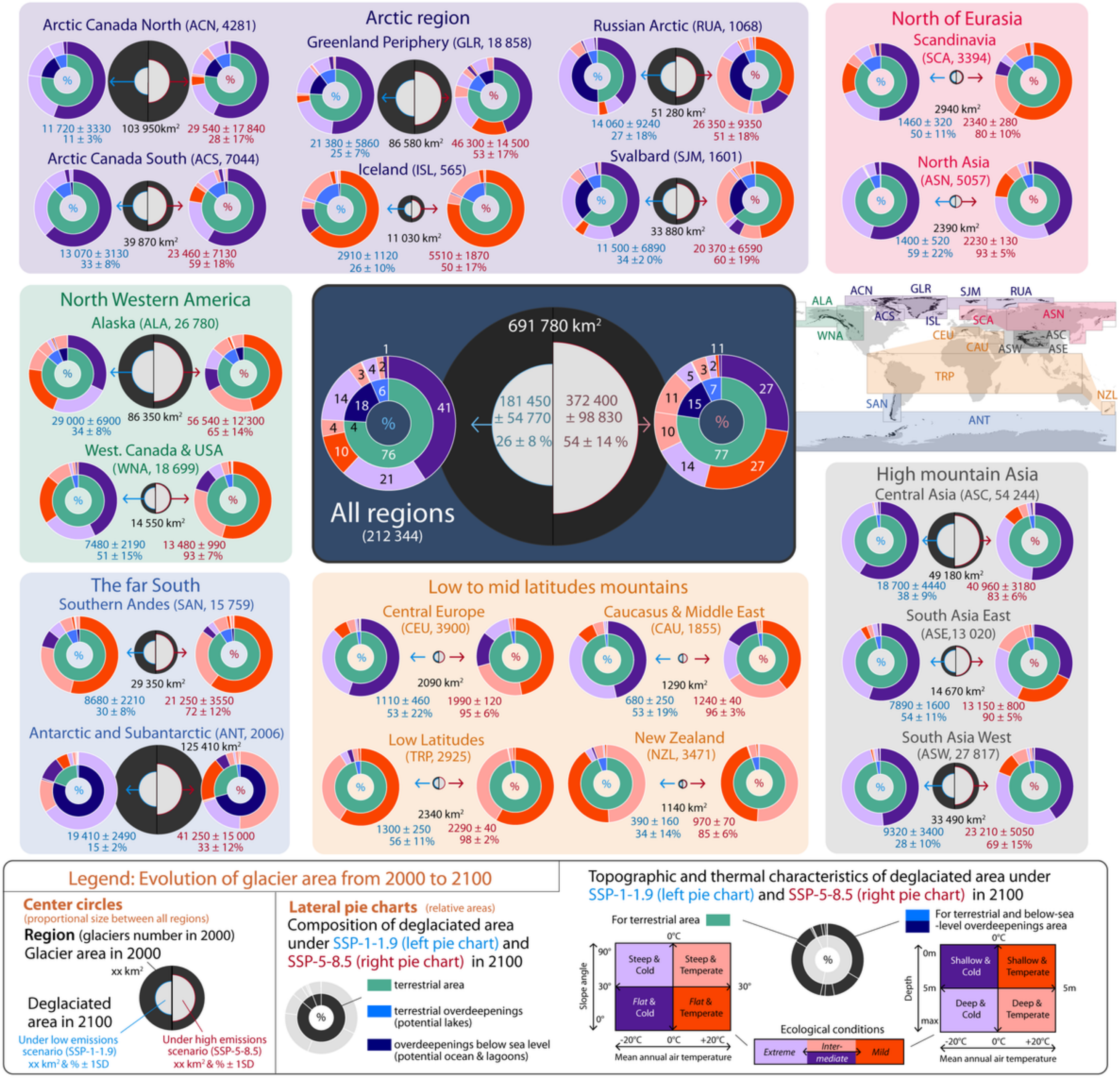

Figure 3

Glaciers, deglaciated areas and topographic and thermal characteristics of deglaciated areas over the 21st century. For each region (geographically grouped for clarity, see location in Fig.2) and globally, the central black circle refers to the 2000 glacier areas and the grey half circles correspond to deglaciated areas in 2100 for the SSP-1-1.9 (low-emission scenario) and 5-8.5 (high–emission scenario). On their left and right, the relative composition and their topographic and thermal characteristics for 2100 are shown for both SSPs. For clarity, we provided mean values for 2100 (associated uncertainties are available in Supplementary Files).

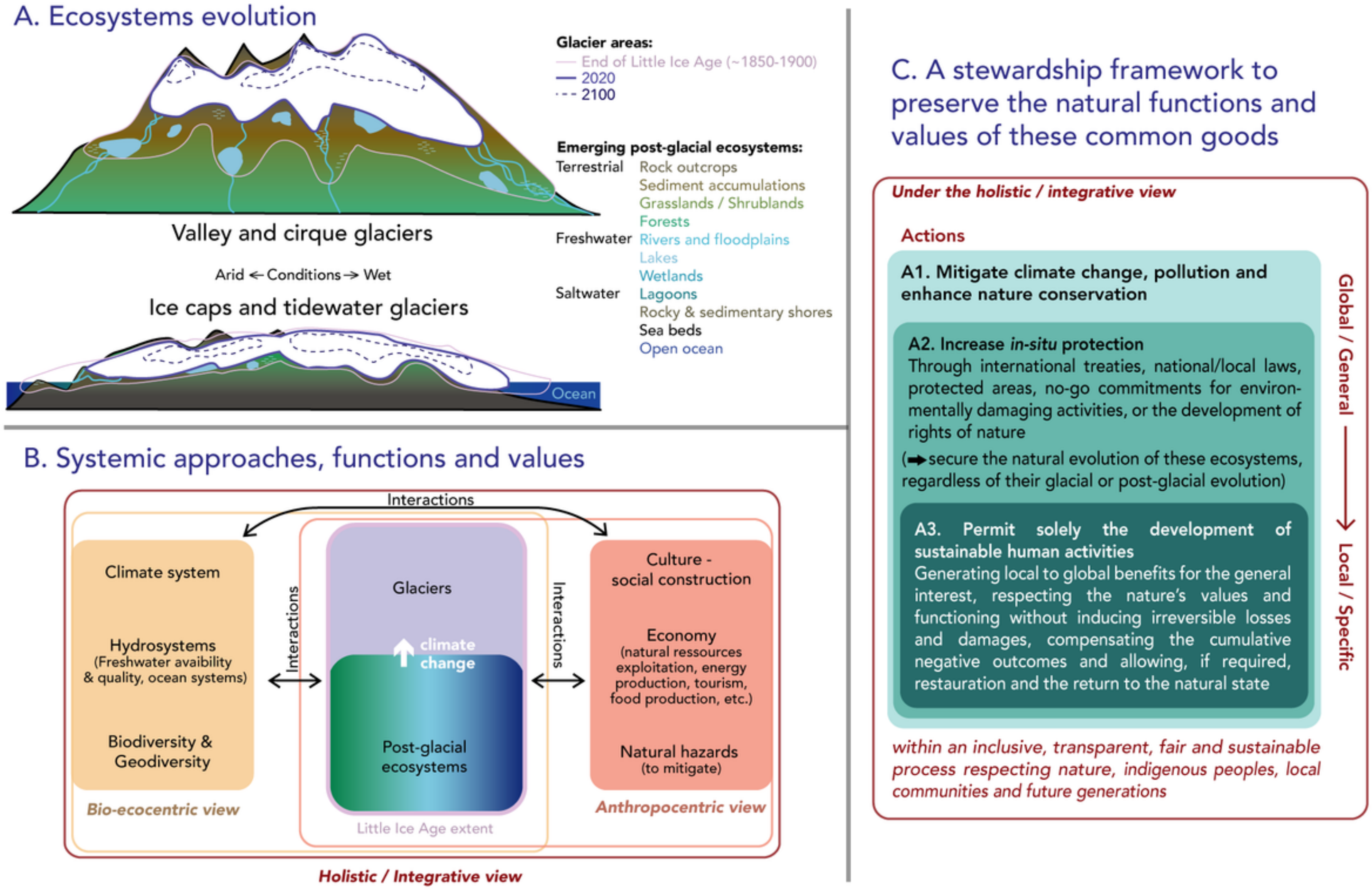

Figure 4

A schematic approach to understand and preserve glaciers and emerging postglacial ecosystems.

Supplementary Files

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