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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 km² 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 km² - 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 (Anaconda 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 km² 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 $664,500 \pm 6060 \text{ km}^2$ 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 ($339,000 \pm 99,000 \text{ km}^2$) are expected to vanish by the end of the century when deglaciation will approach $50,000 \pm 10,000 \text{ km}^2/\text{decade}$. 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 $10,000 \text{ km}^2/\text{decade}$ after 2080 and $78 \pm 8\%$ of the 2020 glacier surface ($517,000 \pm 55,000 \text{ km}^2$) 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 $149,000 \pm 55,000$ (the area of Nepal) to $339,000 \pm 99,000 \text{ km}^2$ (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 $\sim 78\%$ of terrestrial areas, and respectively $\sim 14\%$ and $\sim 8\%$ 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 ($\geq 7,600 \pm 1,700 \text{ km}^2$ and $66 \pm 28 \%$ of the deglaciated surface in 2100; Tab.S1 & Fig.S6), Russian Arctic ($\geq 5,500 \pm 3,600 \text{ km}^2$ and $39 \pm 11 \%$ respectively) and Svalbard ($\geq 3,100 \pm 1,800 \text{ km}^2$ and $26 \pm 6 \%$ respectively). Cumulated terrestrial overdeepenings areas are expected to be large by 2100 in Alaska ($\geq 2,230 \pm 1,150 \text{ km}^2$; Tab.S1 & Fig. S7), Greenland Periphery ($\geq 1,940 \pm 2,140 \text{ km}^2$) and Arctic Canada South ($\geq 1,260 \pm 470 \text{ km}^2$), and represent a significant fraction of the deglaciated areas in Iceland ($\geq 18 \pm 6 \%$) and Scandinavia ($\geq 13 \pm 3 \%$).

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, $\sim 70\%$ of emerging terrestrial areas in 2100 (*i.e.* $80,550 \pm 31,000$ to $188,550 \pm 58,000 \text{ km}^2$ 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 $2,570 \pm 1,030$ to $6,050 \pm 2,000 \text{ km}^2$. 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 $-5,75^\circ\text{C}$; Fig.1E, Tab.S2), or under milder conditions in the high-emission scenario (with respective values $> 55\%$ and $-0,25^\circ\text{C}$). Due to their formation in the thalweg of deglaciated areas, the situation will be similar but warmer for overdeepenings: $\sim 75\%$ of the 2100 their surface will have negative MAAT (median: $-3,75^\circ\text{C}$, Fig.1F, Tab.S2) under the low-emission scenario. Respective values will be $\sim 35\%$ and $+2,25^\circ\text{C}$ 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, $148,100 \pm 28,500$ ($71 \pm 14 \%$) to $33,900 \pm 24,000$ ($16 \pm 11 \%$) 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 $79,800 \pm 29,500$ to $185,100 \pm 44,500$ in 2100 (Tab.S1; Fig.S20-21). Their numbers will be especially large ($\geq 8,000$ in 2100) in Greenland Periphery, Alaska and Central Asia.

Glaciers are expected to store $106,640 \pm 9810$ to $72,650 \pm 22,490$ km³ 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 ($\geq 3,800$ km³) 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 $3,940 \pm 690$ to $8,960 \pm 2040$ km³ 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 km² 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 km³ 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 matter fluxes, emerging overdeepenings 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 steinboeckii* 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*, Muhlfield et

al., 2020; Pacific Salmon, 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 km² 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 km² 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 (Anaconda 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 $181,000 \pm 55,000$ to $372,000 \pm 99,000$ km² 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.

References

1. Albert, J. S., Destouni, G., Duke-Sylvester, S. M., Magurran, A. E., Oberdorff, T., Reis, R. E., ... & Ripple, W. J. (2020). Scientists' warning to humanity on the freshwater biodiversity crisis. *Ambio*, 1-10.
2. Anaconda, P. I., Kinney, J., Schaefer, M., Harrison, S., Wilson, R., Segovia, A., ... & Glasser, N. F. (2018). Glacier protection laws: Potential conflicts in managing glacial hazards and adapting to climate change. *Ambio*, 47(8), 835-845.
3. Anderegg, W. R., Wu, C., Acil, N., Carvalhais, N., Pugh, T. A., Sadler, J. P., & Seidl, R. (2022). A climate risk analysis of Earth's forests in the 21st century. *Science*, 377(6610), 1099-1103.
4. Aubert, J. (1956) *Andiperla willinki* n.sp., Plécoptère nouveau des Andes de Patagonie. *Mitteilungen der Schweizerischen Entomologischen Gesellschaft* 29(2), 229-232.

5. Bollati, I. M., Viani, C., Masseroli, A., Mortara, G., Testa, B., Tronti, G., ... & Reynard, E. (2022). Geodiversity of proglacial areas and implications for geosystem services: A review. *Geomorphology*, 108517.
6. Bosson, J.-B., Huss, M., & Osipova, E. (2019). Disappearing world heritage glaciers as a keystone of nature conservation in a changing climate. *Earth's Future*, 7(4), 469-479.
7. Bosson, J. B., Bal, B., Billant, O., & Wirtz, L. (2020). Fondements scientifiques en vue de la création d'une zone de protection d'habitat naturel du Mont-Blanc - Site d'exception. Asters, Conservatoire d'Espaces Naturels de Haute-Savoie, 51p.
8. Boyd, D. R. (2017). *The rights of nature: A legal revolution that could save the world*. ECW Press.
9. Bradshaw, C. J., Ehrlich, P. R., Beattie, A., Ceballos, G., Crist, E., Diamond, J., ... & Blumstein, D. T. (2021). Underestimating the challenges of avoiding a ghastly future. *Frontiers in Conservation Science*, 9.
10. Carrivick, J. L., & Tweed, F. S. (2013). Proglacial lakes: character, behaviour and geological importance. *Quaternary Science Reviews*, 78, 34-52.
11. Carrivick, J. L., Heckmann, T., Turner, A., & Fischer, M. (2018). An assessment of landform composition and functioning with the first proglacial systems dataset of the central European Alps. *Geomorphology*, 321, 117-128.
12. Cauvy-Fraunié, S., & Dangles, O. (2019). A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution*, 3(12), 1675-1685.
13. CBD (Convention on Biological Diversity) (2022). Nations adopt four goals and 23 targets for 2030 in landmark UN Biodiversity Agreement. *CBD press release 19.12.22*.
14. Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (2016). Nature-based solutions to address global societal challenges. *IUCN: Gland, Switzerland*, 97.
15. Cui, X., Mucci, A., Bianchi, T. S., He, D., Vaughn, D., Williams, E. K., ... & Rosenheim, B. E. (2022). Global fjords as transitory reservoirs of labile organic carbon modulated by organo-mineral interactions. *Science Advances*, 8(46), eadd0610.
16. Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., & Hansen, M. C. (2018). Classifying drivers of global forest loss. *Science*, 361(6407), 1108-1111.
17. Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., ... & Zayas, C. N. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science*, 366(6471), eaax3100.
18. Dinerstein, E., Joshi, A. R., Vynne, C., Lee, A. T. L., Pharand-Deschênes, F., França, M., ... & Olson, D. (2020). A "Global Safety Net" to reverse biodiversity loss and stabilize Earth's climate. *Science advances*, 6(36), eabb2824.
19. Dudley, N., Hockings, M., & Verschuuren, B. (2015). To go, or not to go? What are business attitudes to the philosophy of no-go policies and protected areas?. *PARKS: the International Journal of Protected Areas and Conservation*, 21(2), 7-10.

20. Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R., Goelzer, H., Seroussi, H., ... & Zwinger, T. (2021). Projected land ice contributions to twenty-first-century sea level rise. *Nature*, *593*(7857), 74-82.
21. Egli, M., Favilli, F., Krebs, R., Pichler, B., & Dahms, D. (2012). Soil organic carbon and nitrogen accumulation rates in cold and alpine environments over 1 Ma. *Geoderma*, *183*, 109-123.
22. Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937-1958.
23. Farinotti, D., Huss, M., Furst, J., Landmann, J., Machguth, H., Maussion, F., and Pandit, A. (2019a). A consensus estimate for the ice thickness distribution of all glaciers on Earth. *Nature Geoscience*, *12*, 168-1973, doi:10.1038/s41561-019-0300-3.
24. Farinotti, D., Round, V., Huss, M., Compagno, L., & Zekollari, H. (2019b). Large hydropower and water-storage potential in future glacier-free basins. *Nature*, *575*(7782), 341-344.
25. Ficetola, G. F., Marta, S., Guerrieri, A., Gobbi, M., Ambrosini, R., Fontaneto, D., ... & Thuiller, W. (2021). Dynamics of ecological communities following current retreat of glaciers. *Annual Review of Ecology, Evolution, and Systematics*, *52*, 405-426.
26. Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., ... & Walker, B. H. (2021). Our future in the Anthropocene biosphere. *Ambio*, *50*(4), 834-869.
27. Gobbi, M., Ambrosini, R., Casarotto, C., Diolaiuti, G., Ficetola, G. F., Lencioni, V., ... & Caccianiga, M. (2021). Vanishing permanent glaciers: climate change is threatening a European Union habitat (Code 8340) and its poorly known biodiversity. *Biodiversity and Conservation*, *30*(7), 2267-2276. Gray, M. (2004). *Geodiversity: valuing and conserving abiotic nature*. John Wiley & Sons.
28. GTN-G (2017): GTN-G Glacier Regions. Global Terrestrial Network for Glaciers. DOI: 10.5904/gtng-glacreg-2017-07. Online access: <http://dx.doi.org/10.5904/gtng-glacreg-2017-07>.
29. Haeberli, W., Buetler, M., Huggel, C., Friedli, T. L., Schaub, Y., & Schleiss, A. J. (2016). New lakes in deglaciating high-mountain regions—opportunities and risks. *Climatic change*, *139*(2), 201-214.
30. Hausammann, F., & Reich, J. (2022). Switzerland—2020 and 2021 Review of Environmental Law: Federal CO2-Act, Bilateral Treaties on ITMOs, and Climate Change Litigation. *Bilateral Treaties on ITMOs, and Climate Change Litigation (February 26, 2022)*.
31. Heer, O. (1837). Die Käfer der Schweiz. Kritische Bemerkungen und Beschreibungen der neuen Arten 2, 1 *Neuchâtel: Petitpierre*, 1-55.
32. Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., ... & Thépaut, J. N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999-2049.
33. Hock, R., Bliss, A., Marzeion, B. E. N., Giesen, R. H., Hirabayashi, Y., Huss, M., ... & Slangen, A. B. (2019). GlacierMIP—A model intercomparison of global-scale glacier mass-balance models and projections. *Journal of Glaciology*, *65*(251), 453-467.
34. Hogg, C. J., Lea, M. A., Soler, M. G., Vasquez, V. N., Payo-Payo, A., Parrott, M. L., ... & Brooks, C. M. (2020). Protect the Antarctic Peninsula—before it's too late. *Nature*, *586*, 496-499.

35. Hotelling, S., Hood, E., & Hamilton, T. L. (2017). Microbial ecology of mountain glacier ecosystems: biodiversity, ecological connections and implications of a warming climate. *Environmental microbiology*, 19(8), 2935-2948.
36. Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., ... & Käab, A. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, 592(7856), 726-731.
37. Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., ... & Mark, B. G. (2017). Toward mountains without permanent snow and ice. *Earth's Future*, 5(5), 418-435.
38. Huss, M., & Hock, R. (2015). A new model for global glacier change and sea-level rise. *Frontiers in Earth Science*, 3, 54.
39. Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, 8(2), 135-140.
40. Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., ... & Emmer, A. (2020). Importance and vulnerability of the world's water towers. *Nature*, 577(7790), 364-369.
41. IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany.
42. IPBES (2022): IPBES Values Assessment – Decisions Based on Narrow Set of Market Values of Nature Underpin the Global Biodiversity Crisis. IPBES secretariat, Bonn, Germany.
43. IPCC (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.
44. IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press,
45. IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.
46. IUCN, UNEP-WCMC (2018). The World Database on Protected Areas (WDPA, 2018); www.protectedplanet.net.
47. Johnson, C. N., Balmford, A., Brook, B. W., Buettel, J. C., Galetti, M., Guangchun, L., & Wilmshurst, J. M. (2017). Biodiversity losses and conservation responses in the Anthropocene. *Science*, 356(6335), 270-275.

48. Kang, S., Zhang, Y., Qian, Y., & Wang, H. (2020). A review of black carbon in snow and ice and its impact on the cryosphere. *Earth-science reviews*, 210, 103346.
49. Keesstra, S., Sannigrahi, S., López-Vicente, M., Pulido, M., Novara, A., Visser, S., & Kalantari, Z. (2021). The role of soils in regulation and provision of blue and green water. *Philosophical Transactions of the Royal Society B*, 376(1834), 20200175.
50. Khedim, N., Cecillon, L., Poulénard, J., Barré, P., Baudin, F., Marta, S., ... & Ficetola, G. F. (2021). Topsoil organic matter build-up in glacier forelands around the world. *Global Change Biology*, 27(8), 1662-1677.
51. Liang, Y. (1979). A new genus and species of Enchytraeidae from Tibet. *Acta Zootaxonom. Sinica*, 4, 312-315.
52. Lee, E., Carrivick, J. L., Quincey, D. J., Cook, S. J., James, W. H., & Brown, L. E. (2021). Accelerated mass loss of Himalayan glaciers since the Little Ice Age. *Scientific reports*, 11(1), 1-8.
53. Linsbauer, A., Huss, M., Hodel, E., Bauder, A., Fischer, M., Weidmann, Y., ... & Schmassmann, E. (2021). The New Swiss Glacier Inventory SGI2016: from a topographical to a glaciological dataset. *Frontiers in Earth Science*, 774.
54. Malles, J. H., & Marzeion, B. (2021). Twentieth century global glacier mass change: an ensemble-based model reconstruction. *The Cryosphere*, 15(7), 3135-3157.
55. Marzeion, B., Hock, R., Anderson, B., Bliss, A., Champollion, N., Fujita, K., ... & Zekollari, H. (2020). Partitioning the uncertainty of ensemble projections of global glacier mass change. *Earth's Future*, 8(7), e2019EF001470.
56. Mateu, J., & Moret, P. (2001) Cinq nouveaux Paratrechus de l'Équateur [Coleoptera, Carabidae, Trechini]. *Revue française d'entomologie (1979)* 23,1: 93-100.
57. Maxwell, S. L., Cazalis, V., Dudley, N., Hoffmann, M., Rodrigues, A. S., Stolton, S., ... & Maron, M. (2020). Area-based conservation in the twenty-first century. *Nature*, 586(7828), 217-227.
58. Mayor, J. R., Sanders, N. J., Classen, A. T., Bardgett, R. D., Clement, J. C., Fajardo, A., ... & Wardle, D. A. (2017). Elevation alters ecosystem properties across temperate treelines globally. *Nature*, 542(7639), 91-95.
59. McKay D.I.A, et al. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*. 377(6611).
60. Meinshausen, M., Nicholls, Z. R., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., ... & Wang, R. H. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, 13(8), 3571-3605.
61. Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., ... & Hodson, A. J. (2017). Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences*, 114(37), 9770-9778.
62. Muhlfeld, C. C., Cline, T. J., Giersch, J. J., Peitzsch, E., Florentine, C., Jacobsen, D., & Hotaling, S. (2020). Specialized meltwater biodiversity persists despite widespread deglaciation. *Proceedings of the National Academy of Sciences*, 117(22), 12208-12214.

63. Peck, L. S., Barnes, D. K., Cook, A. J., Fleming, A. H., & Clarke, A. (2010). Negative feedback in the cold: ice retreat produces new carbon sinks in Antarctica. *Global Change Biology*, *16*(9), 2614-2623.
64. Pekel, J. F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, *540*(7633), 418-422.
65. Pi, X., Luo, Q., Feng, L., Xu, Y., Tang, J., Liang, X., ... & Bryan, B. A. (2022). Mapping global lake dynamics reveals the emerging roles of small lakes. *Nature communications*, *13*(1), 1-12.
66. Pitman, K. J., Moore, J. W., Huss, M., Sloat, M. R., Whited, D. C., Beechie, T. J., ... & Schindler, D. E. (2021). Glacier retreat creating new Pacific salmon habitat in western North America. *Nature Communications*, *12*(1), 1-10.
67. Pörtner, H. O., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., ... & Ngo, H. (2021). Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change.
68. RGI Consortium, 2017. Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 6. [Indicate subset used]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: <https://doi.org/10.7265/4m1f-gd79>
69. Richardson, D. C., Holgerson, M. A., Farragher, M. J., Hoffman, K. K., King, K., Alfonso, M. B., ... & Sweetman, J. N. (2022). A functional definition to distinguish ponds from lakes and wetlands. *Scientific reports*, *12*(1), 1-13.
70. Ripple, W. J., Wolf, C., Newsome, T. M., Galetti, M., Alamgir, M., Crist, E., ... & 15,364 scientist signatories from 184 countries. (2017). World scientists' warning to humanity: A second notice. *BioScience*, *67*(12), 1026-1028.
71. Roe, G. H., Christian, J. E., & Marzeion, B. (2021). On the attribution of industrial-era glacier mass loss to anthropogenic climate change. *The Cryosphere*, *15*(4), 1889-1905.
72. Roelfsema, M., van Soest, H. L., Harmsen, M., van Vuuren, D. P., Bertram, C., den Elzen, M., ... & Vishwanathan, S. S. (2020). Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nature communications*, *11*(1), 1-12.
73. Rosero, P., Crespo-Pérez, V., Espinosa, R., Andino, P., Barragán, Á., Moret, P., ... & Cauvy-Fraunié, S. (2021). Multi-taxa colonisation along the foreland of a vanishing equatorial glacier. *Ecography*, *44*(7), 1010-1021.
74. Rounce, D., Maussion, F., Hock, R., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L., Copland, L., Farinotti, D., Menounos, B., McNabb, R.W. (in press). Global glacier change in the 21st century: Every tenth of a degree temperature increase matters. *Science*.
75. Rumpf, S. B., Gravey, M., Brönnimann, O., Luoto, M., Cianfrani, C., Mariethoz, G., & Guisan, A. (2022). From white to green: Snow cover loss and increased vegetation productivity in the European Alps. *Science*, *376*(6597), 1119-1122.
76. Senf, C., & Seidl, R. (2021). Mapping the forest disturbance regimes of Europe. *Nature Sustainability*, *4*(1), 63-70.
77. Shugar, D. H., Clague, J. J., Best, J. L., Schoof, C., Willis, M. J., Copland, L., & Roe, G. H. (2017). River piracy and drainage basin reorganization led by climate-driven glacier retreat. *Nature Geoscience*,

10(5), 370-375.

78. Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., ... & Strattman, K. (2020). Rapid worldwide growth of glacial lakes since 1990. *Nature Climate Change*, 10(10), 939-945.
79. Shukla, P. R., Skeg, J., Buendia, E. C., Masson-Delmotte, V., Pörtner, H. O., Roberts, D. C., ... & Malley, J. (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.
80. Sigdel, S. R., Zhang, H., Zhu, H., Muhammad, S., & Liang, E. (2020). Retreating glacier and advancing forest over the past 200 years in the Central Himalayas. *Journal of Geophysical Research: Biogeosciences*, 125(9), e2020JG005751.
81. St-Pierre, K. A., St-Louis, V. L., Schiff, S. L., Lehnerr, I., Dainard, P. G., Gardner, A. S., ... & Sharp, M. J. (2019). Proglacial freshwaters are significant and previously unrecognized sinks of atmospheric CO₂. *Proceedings of the National Academy of Sciences*, 116(36), 17690-17695.
82. Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., ... & Donges, J. F. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, 115(33), 8252-8259.
83. Stibal, M., Bradley, J. A., Edwards, A., Hotaling, S., Zawierucha, K., Rosvold, J., ... & Šabacká, M. (2020). Glacial ecosystems are essential to understanding biodiversity responses to glacier retreat. *Nature Ecology & Evolution*, 4(5), 686-687.
84. Towns, D. L., & William L. P. (1996). Leptophlebiidae (Insecta: Ephemeroptera). *Fauna of New Zealand*, 36, 144 pp.
85. UNEP-WCMC, IUCN (2022). *Protected Planet: The World Database on Protected Areas (WDPA)*. <https://www.protectedplanet.net/en>.
86. UNESCO, IUCN (2022). *World Heritage Glaciers: Sentinels of climate change*, Paris, UNESCO; Gland, IUCN
87. Wang-Erlandsson, L., Tobian, A., van der Ent, R. J., Fetzer, I., te Wierik, S., Porkka, M., ... & Rockström, J. (2022). A planetary boundary for green water. *Nature Reviews Earth & Environment*, 1-13.
88. Watson, J. E., Venter, O., Lee, J., Jones, K. R., Robinson, J. G., Possingham, H. P., & Allan, J. R. (2018). Protect the last of the wild.
89. Winterbourn, M. J., Cadbury, S., Ilg, C., Milner, A. M. (2008). Mayfly production in a New Zealand glacial stream and the potential effect of climate change. *Hydrobiologia*, 603(1), 211-219.
90. Wu, J., Mollenhauer, G., Stein, R., Köhler, P., Hefter, J., Fahl, K., ... & Nam, S. I. (2022). Deglacial release of petrogenic and permafrost carbon from the Canadian Arctic impacting the carbon cycle. *Nature Communications*, 13(1), 1-11.
91. Xu, C., Kohler, T. A., Lenton, T. M., Svenning, J. C., & Scheffer, M. (2020). Future of the human climate niche. *Proceedings of the National Academy of Sciences*, 117(21), 11350-11355.

92. Zimmer, A., Beach, T., Klein, J. A., & Recharte Bullard, J. (2022). The need for stewardship of lands exposed by deglaciation from climate change. *Wiley Interdisciplinary Reviews: Climate Change*, 13(2), e753.

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 $>0.005 \text{ km}^2$ and depths $>3 \text{ m}$ 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 overdeepenings, 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 ($>0.005 \text{ km}^2$) and depth ($>3 \text{ m}$) 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 deglaciaded areas above sea level, were considered as terrestrial areas.

The characteristics of the deglaciaded 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 deglaciaded 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 deglaciaded 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 fluvio-glacial 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.

Method's references

1. Ballantyne, C. K. (2002). Paraglacial geomorphology. *Quaternary Science Reviews*, 21(18-19), 1935-2017.
2. Bianchi, T. S., Arndt, S., Austin, W. E., Benn, D. I., Bertrand, S., Cui, X., ... & Syvitski, J. (2020). Fjords as aquatic critical zones (ACZs). *Earth-Science Reviews*, 203, 103145.

3. Carrivick, J. L., & Tweed, F. S. (2013). Proglacial lakes: character, behaviour and geological importance. *Quaternary Science Reviews*, 78, 34-52.
4. Cauvy-Fraunié, S., & Dangles, O. (2019). A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution*, 3(12), 1675-1685.
5. Compagno, L, Zekollari, H., Huss, M., and Farinotti, F. (2021). Limited impact of various climate datasets on future glacier evolution in Scandinavia and Iceland. *Journal of Glaciology*, 1, 1-17, doi:10.1017/jog.2021.24.
6. Compagno, L., Huss, M., Zekollari, H., Miles, E. S., & Farinotti, D. (2022). Future growth and decline of high mountain Asia's ice-dammed lakes and associated risk. *Communications Earth & Environment*, 3(1), 1-9.
7. Egli, M., Favilli, F., Krebs, R., Pichler, B., & Dahms, D. (2012). Soil organic carbon and nitrogen accumulation rates in cold and alpine environments over 1 Ma. *Geoderma*, 183, 109-123.
8. Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9(5), 1937-1958.
9. Farinotti, D., Huss, M., Fuerst, J., Landmann, J., Machguth, H., Maussion, F., and Pandit, A. (2019). A consensus estimate for the ice thickness distribution of all glaciers on Earth. *Nature Geoscience*, 12, 168-1973, doi:10.1038/s41561-019-0300-3.
10. GTN-G (2017): GTN-G Glacier Regions. Global Terrestrial Network for Glaciers. DOI: 10.5904/gtng-glacreg-2017-07. Online access: <http://dx.doi.org/10.5904/gtng-glacreg-2017-07>.
11. Haeberli, W., Buetler, M., Huggel, C., Friedli, T. L., Schaub, Y., & Schleiss, A. J. (2016). New lakes in deglaciating high-mountain regions—opportunities and risks. *Climatic change*, 139(2), 201-214.
12. Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., ... & Thépaut, J. N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999-2049.
13. Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., ... & Käab, A. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, 592(7856), 726-731.
14. Huss, M., Jouvét, G., Farinotti, D., & Bauder, A. (2010). Future high-mountain hydrology: a new parameterization of glacier retreat. *Hydrology and Earth System Sciences*, 14(5), 815-829.
15. Huss, M., & Hock, R. (2015). A new model for global glacier change and sea-level rise. *Frontiers in Earth Science*, 3, 54.
16. Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, 8(2), 135-140.
17. Hock, R. (2003). Temperature index melt modelling in mountain areas. *Journal of hydrology*, 282(1-4), 104-115.
18. Khedim, N., Cecillon, L., Poulénard, J., Barré, P., Baudin, F., Marta, S., ... & Ficetola, G. F. (2021). Topsoil organic matter build-up in glacier forelands around the world. *Global Change Biology*, 27(8), 1662-

1677.

19. Lee, E., Carrivick, J. L., Quincey, D. J., Cook, S. J., James, W. H., & Brown, L. E. (2021). Accelerated mass loss of Himalayan glaciers since the Little Ice Age. *Scientific reports*, *11*(1), 1-8.
20. Linsbauer, A., Paul, F., & Haeberli, W. (2012). Modelling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. *Journal of Geophysical Research: Earth Surface*, *117*(F3).
21. Marzeion, B., Hock, R., Anderson, B., Bliss, A., Champollion, N., Fujita, K., ... & Zekollari, H. (2020). Partitioning the uncertainty of ensemble projections of global glacier mass change. *Earth's Future*, *8*(7), e2019EF001470.
22. Mayor, J. R., Sanders, N. J., Classen, A. T., Bardgett, R. D., Clement, J. C., Fajardo, A., ... & Wardle, D. A. (2017). Elevation alters ecosystem properties across temperate treelines globally. *Nature*, *542*(7639), 91-95.
23. Meinshausen, M., Nicholls, Z. R., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., ... & Wang, R. H. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, *13*(8), 3571-3605.
24. Millan, R., Mougnot, J., Rabatel, A., & Morlighem, M. (2022). Ice velocity and thickness of the world's glaciers. *Nature Geoscience*, *15*(2), 124-129.
25. Muñoz, R., Huggel, C., Frey, H., Cochachin, A., & Haeberli, W. (2020). Glacial lake depth and volume estimation based on a large bathymetric dataset from the Cordillera Blanca, Peru. *Earth surface processes and landforms*, *45*(7), 1510-1527.
26. O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., ... & Zhang, G. (2015). Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, *42*(24), 10-773.
27. Oerlemans, J., & Nick, F. M. (2005). A minimal model of a tidewater glacier. *Annals of Glaciology*, *42*, 1-6.
28. Peck, L. S., Barnes, D. K., Cook, A. J., Fleming, A. H., & Clarke, A. (2010). Negative feedback in the cold: ice retreat produces new carbon sinks in Antarctica. *Global Change Biology*, *16*(9), 2614-2623.
29. Pitman, K. J., Moore, J. W., Huss, M., Sloat, M. R., Whited, D. C., Beechie, T. J., ... & Schindler, D. E. (2021). Glacier retreat creating new Pacific salmon habitat in western North America. *Nature Communications*, *12*(1), 1-10.
30. Pörtner, H. O., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., ... & Ngo, H. (2021). Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change.
31. RGI Consortium, 2017. Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 6. [Indicate subset used]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: <https://doi.org/10.7265/4m1f-gd79>
32. Rounce, D., Maussion, F., Hock, R., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L., Copland, L., Farinotti, D., Menounos, B., McNabb, R.W. (in press). Global glacier change in the 21st century: Every tenth of a degree temperature increase matters. *Science*.

33. Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., ... & Strattman, K. (2020). Rapid worldwide growth of glacial lakes since 1990. *Nature Climate Change*, *10*(10), 939-945.
34. Sommaruga, R. (2015). When glaciers and ice sheets melt: consequences for planktonic organisms. *Journal of plankton research*, *37*(3), 509-518.
35. Steffen, T., Huss, M., Estermann, R., Hodel, E., and Farinotti, D. (2022). Volume, evolution, and sedimentation of future glacier lakes in Switzerland over the 21st century. *Earth Surface Dynamics*, *10*, 723-741, doi:10.5194/esurf-10-723-2022.
36. UNEP-WCMC, IUCN (2022). *Protected Planet: The World Database on Protected Areas (WDPA)*.<https://www.protectedplanet.net/en>.
37. Welty, E., Zemp, M., Navarro, F., Huss, M., Fürst, J. J., Gärtner-Roer, I., ... & Contributors, G. (2020). Worldwide version-controlled database of glacier thickness observations. *Earth System Science Data*, *12*(4), 3039-3055.
38. Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O'Reilly, C. M., & Sharma, S. (2020). Global lake responses to climate change. *Nature Reviews Earth & Environment*, *1*(8), 388-403.

Figures

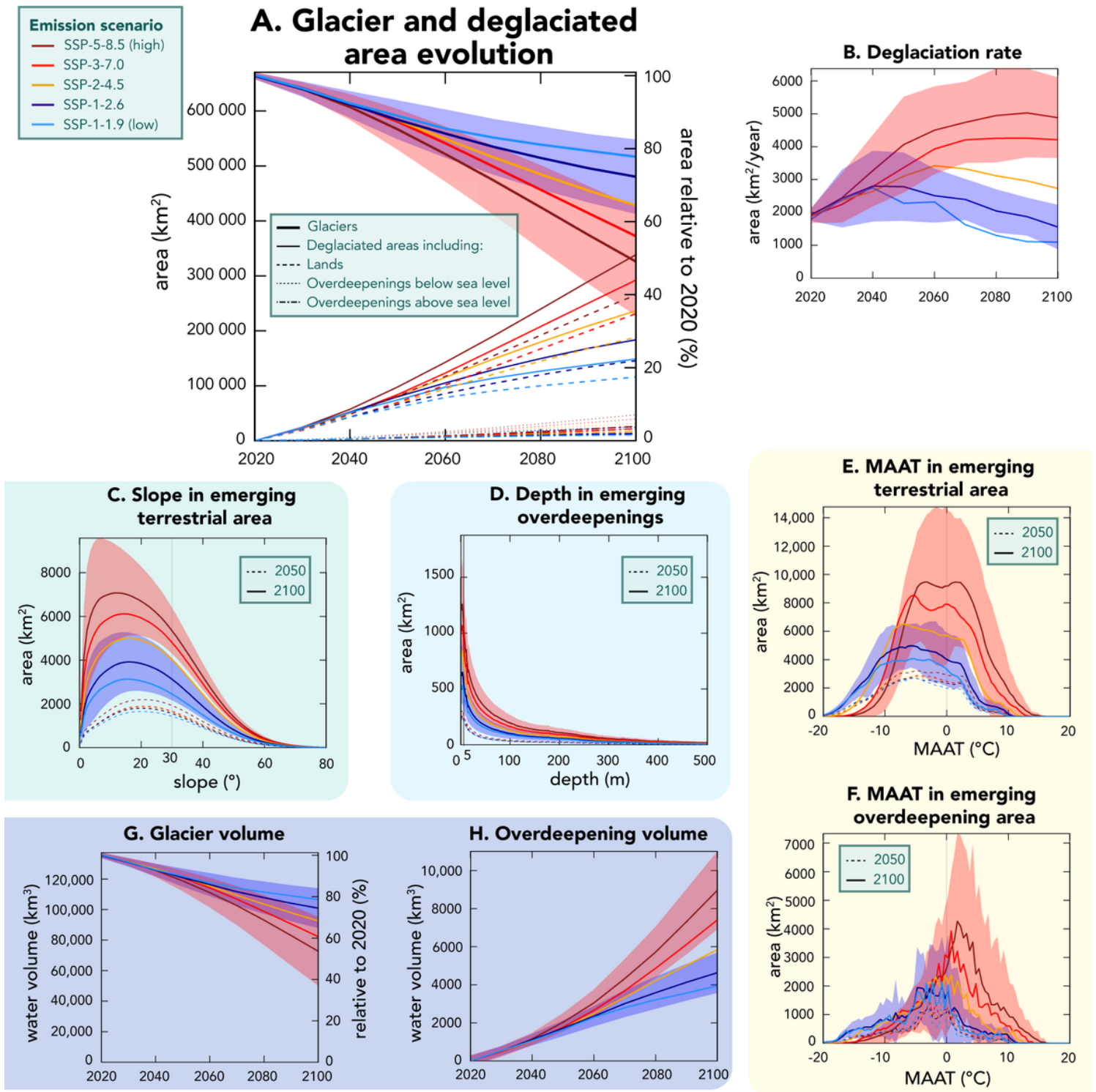


Figure 1

Future evolution of glacier and deglaciating areas (A), deglaciating rate (B), glacier and overdeepenings volume (G, H), slope and depth (C, D), and mean annual air temperature in emerging deglaciating 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 ($\pm 1\sigma$) 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 deglaciating areas are not displayed for clarity. Plots D, F and H show results for both overdeepenings below and above sea level. MAAT in emerging deglaciating areas (E, F) were computed as average values over the 2000-2100 period.

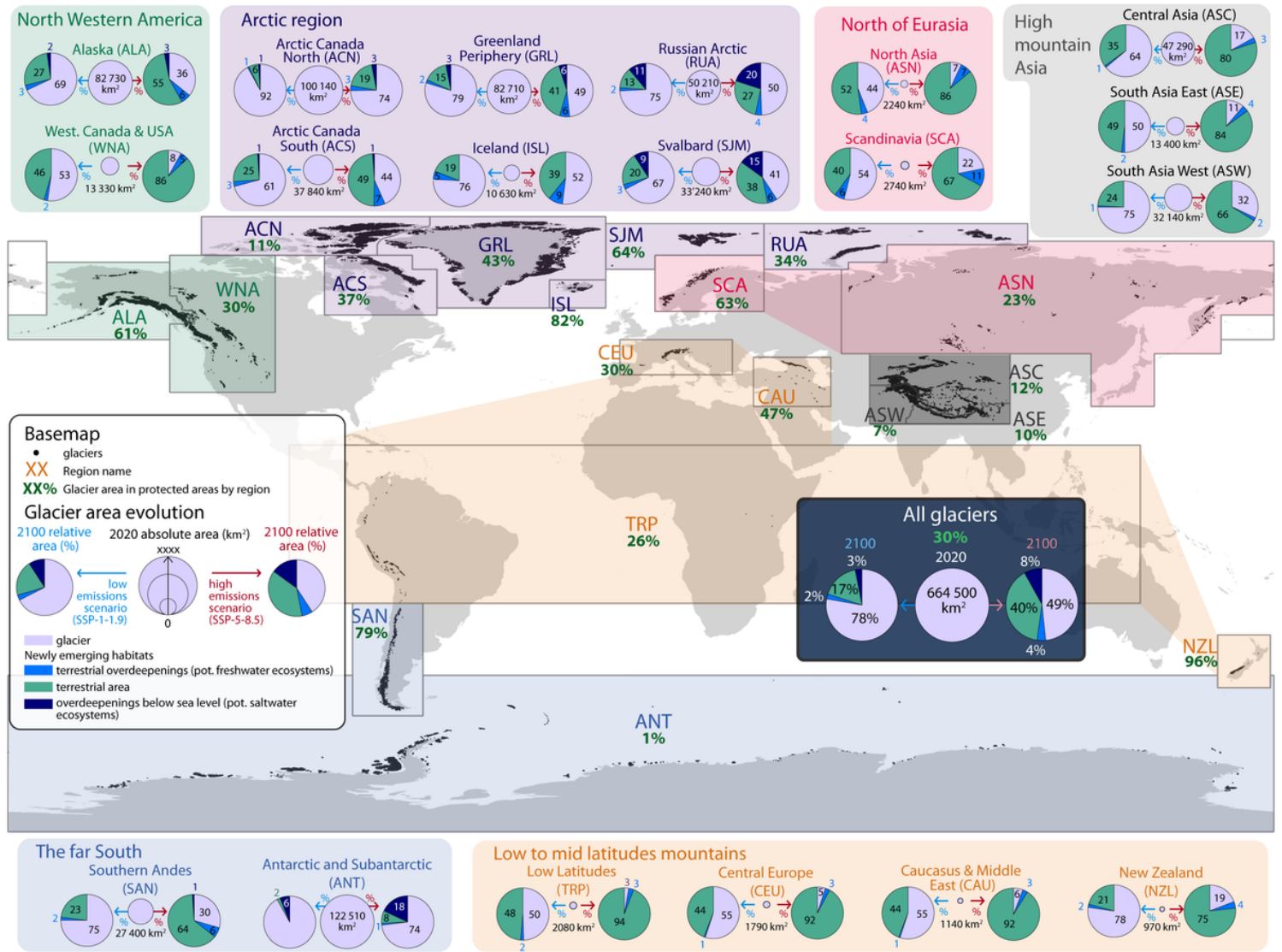


Figure 2

Distribution of glaciers and deglaciating 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.

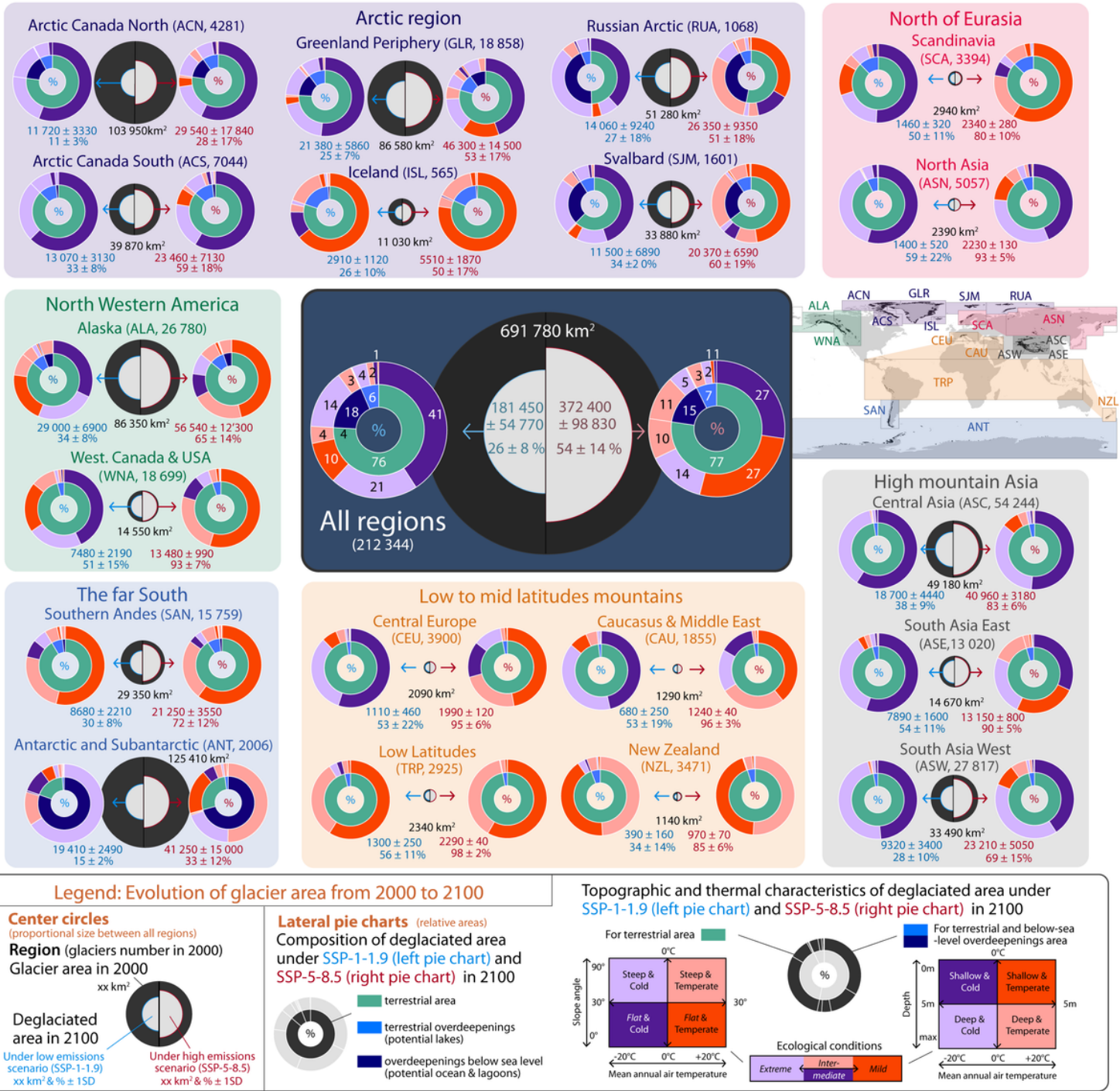
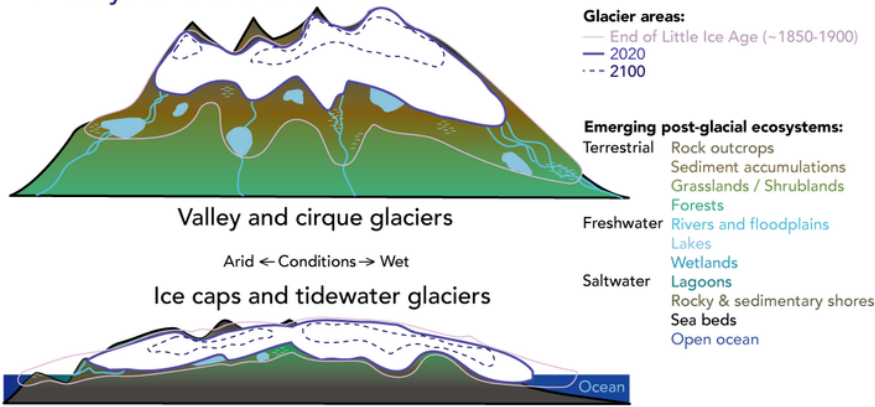


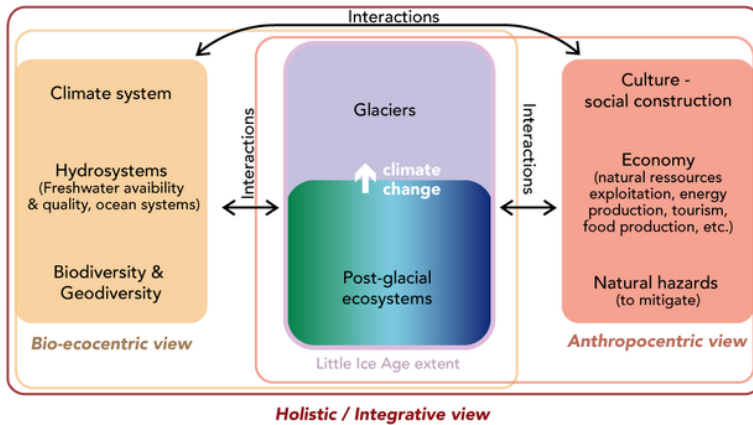
Figure 3

Glaciers, deglaciating areas and topographic and thermal characteristics of deglaciating 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 deglaciating 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).

A. Ecosystems evolution



B. Systemic approaches, functions and values



C. A stewardship framework to preserve the natural functions and values of these common goods

Under the holistic / integrative view

Actions

A1. Mitigate climate change, pollution and enhance nature conservation

A2. Increase *in-situ* protection
Through international treaties, national/local laws, protected areas, no-go commitments for environmentally damaging activities, or the development of rights of nature

(→ secure the natural evolution of these ecosystems, regardless of their glacial or post-glacial evolution)

A3. Permit solely the development of sustainable human activities

Generating local to global benefits for the general interest, respecting the nature's values and functioning without inducing irreversible losses and damages, compensating the cumulative negative outcomes and allowing, if required, restoration and the return to the natural state

within an inclusive, transparent, fair and sustainable process respecting nature, indigenous peoples, local communities and future generations

Global / General
↓
Local / Specific

Figure 4

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

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryFiles.zip](#)