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We Must Stop Fossil Fuel Emissions to Protect Permafrost Ecosystems

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Climate change is an existential threat to the vast global permafrost domain. The diverse human cultures, ecological communities, and biogeochemical cycles of this tenth of the planet depend on the persistence of frozen conditions. The complexity, immensity, and remoteness of permafrost ecosystems make it difficult to grasp how quickly things are changing and what can be done about it. Here, we summarize terrestrial and marine changes in the permafrost domain with an eye toward global policy. While many questions remain, we know that continued fossil fuel burning is incompatible with the continued existence of the permafrost domain as we know it. If we fail to protect permafrost ecosystems, the consequences for human rights, biosphere integrity, and global climate will be severe. The policy implications are clear: the faster we reduce human emissions and draw down atmospheric CO_2, the more of the permafrost domain we can save. Emissions reduction targets must be strengthened and accompanied by support for local peoples to protect intact ecological communities and natural carbon sinks within the permafrost domain. Some proposed geoengineering interventions such as solar shading, surface albedo modification, and vegetation manipulations are unproven and may exacerbate environmental injustice without providing lasting protection. Conversely, astounding advances in renewable energy have reopened viable pathways to halve human greenhouse gas emissions by 2030 and effectively stop them well before 2050. We call on leaders, corporations, researchers, and citizens everywhere to acknowledge the global importance of the permafrost domain and work towards climate restoration and empowerment of Indigenous and immigrant communities in these regions.

Keywords: permafrost climate feedback, Arctic, Boreal, climate policy, renewable energy, ecosystem feedback, Earth stewardship, permafrost domain

INTRODUCTION

Though permafrost-affected regions cover only 10% of Earth's surface, they constitute more than half of all remaining terrestrial and marine wilderness (Watson et al., 2018), making them crucial to maintaining biosphere integrity in our rapidly changing world. These regions, which we refer to as the permafrost domain (**Figure 1**), contain between 2.5 and 3 trillion tons of organic carbon—more than all of Earth's other life, soil, and atmosphere combined (Hugelius et al., 2014; Abbott et al., 2016b; Sayedi et al., 2020; Mishra et al., 2021; Abbott B. W., 2022; Schuur et al., 2022). The permafrost domain is home to tens of millions of people, including diverse Indigenous and immigrant cultures that both depend on and sustain these globally-significant ecosystems (Riedlinger and Berkes, 2001; Parkinson and Berner, 2009; Pearce et al., 2009; Chapin et al., 2013; Díaz et al., 2019; Proverbs et al., 2020; Ellis et al., 2021; Mettiäinen et al., 2022). The permafrost domain's three-fold importance—biodiversity, climate, and human peoples—means that governments, corporations, and communities within and outside of these regions must commit to preventing dangerous environmental change (Chapin and Díaz, 2020; Whyte, 2020; Chapin, 2021; Natali et al., 2021; Arctic Council, 2022).

The permafrost domain is uniquely vulnerable to climate change because of accelerated warming and the prevalence of ice. Air temperature in the permafrost domain over land and sea has risen two to four times faster than the global mean, largely because of ice and snow loss, changes in ocean and atmospheric circulation, and the effects of ozone-depleting gases (Huang et al., 2017; Goosse et al., 2018; Mu et al., 2020a; Polvani et al., 2020; AMAP, 2021). Ice in all its forms underpins and overlays the permafrost domain, and its loss disrupts energy balance, ecosystem structure, and human activity (Bamber et al., 2018; Schuur and Mack, 2018; Bamber et al., 2019; Turetsky et al., 2020; Schmidt et al., 2021; Irrgang et al., 2022). Consequently, climate change is intensifying disturbance regimes across the permafrost domain and restructuring socioecological dynamics at continental scales (Hjort et al., 2018; Chou et al., 2021; Veraverbeke et al., 2021; Treharne et al., 2022). In many regions, these changes are progressing decades faster than expected (Farquharson et al., 2019; Angelopoulos et al., 2021; Parkinson and DiGirolamo, 2021), likely heralding the transition of the permafrost domain into unprecedented biophysical and socioecological states (Box et al., 2019; IPCC, 2019; Meredith et al., 2019; Chen et al., 2021).

Pervasive and interconnected changes in the permafrost domain are triggering complex local biogeochemical responses with global repercussions. The ongoing release of large amounts of greenhouse gas (GHG) from permafrost soils, sediments, and waterways has motivated substantial research and attracted public attention (Schuur et al., 2015; Andreassen et al., 2017; Kessler, 2017; Froitzheim et al., 2021; Treharne et al., 2022). The production and release of CO_2, CH_4, and N_2O occur during the decomposition or combustion of organic matter in terrestrial and aquatic environments (Schädel et al., 2016; Plaza et al., 2019; Voigt et al., 2020; Abbott B. W., 2022). Additionally, CH_4 can escape from subsea or subterranean fossil reserves or hydrate deposits, particularly during disturbance from permafrost thaw or fossil-fuel exploration and extraction (Walter et al., 2008; Thornton et al., 2016; Behari et al., 2020; Sayedi et al., 2020; Froitzheim et al., 2021).

The release of GHGs and loss of surface ice and snow from the permafrost domain constitute some of the largest destabilizing climate feedbacks globally (Schaefer et al., 2012; Schuur et al., 2015; Hugelius, 2022). These feedbacks are very likely to be nonlinear, with the amount of GHG production and albedo change often exponentially related to temperature (Abbott et al., 2016b; Carey et al., 2016; Turetsky et al., 2020; AMAP, 2021). The potential magnitude and timing of such amplifying permafrost climate feedbacks remain highly uncertain but could amount to several hundred gigatons (Gt) of CO_2 equivalent over the next two centuries (Schuur et al., 2015, 2022; McGuire et al., 2018; Meredith et al., 2019; Sayedi et al., 2020; Canadell et al., 2021). GHG emissions from the permafrost domain are already similar to the annual emissions of Japan (Hugelius, 2022). Until recently, permafrost domain GHG release was omitted from the Earth system models (ESMs) used to predict climate change trajectories and inform international climate targets (Canadell et al., 2021; Natali et al., 2021). New ESMs are beginning to integrate permafrost carbon feedbacks, but estimates remain preliminary and lack a number of important processes (Abbott et al., 2016b; McGuire et al., 2018; Chen et al., 2020; de Vrese and Brovkin, 2021; Natali et al., 2021).

The combination of growing scientific attention and persistent socio-ecological complexity has created polarized and incomplete perceptions about permafrost in public and policymaker circles

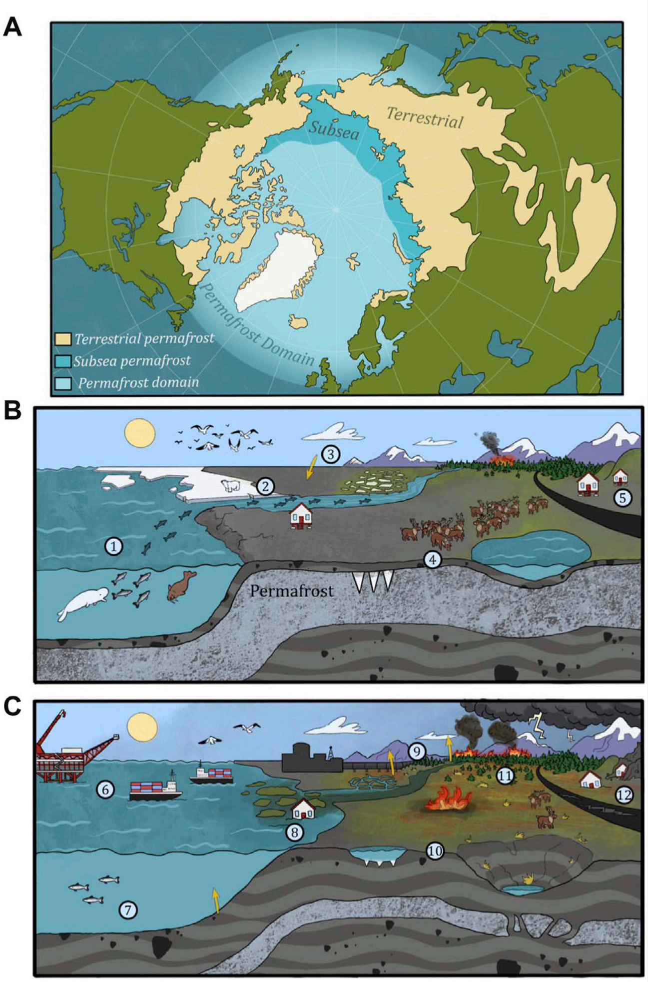

FIGURE 1 | The extent and example futures of the permafrost domain **(A)** Our definition of the domain includes marine and terrestrial regions substantially affected by perennial frozen material, including oceans and seas above 50°N, subsea permafrost on the continental shelves, Arctic tundra, Boreal forest, and Alpine permafrost. The figure shows potential permafrost futures for **(B)** a rapid decarbonization scenario and **(C)** a continued fossil energy scenario. Panel B depicts: 1. Resilient biological communities in marine, coastal, and terrestrial environments, 2. Persistence of sea ice, especially crucial multiyear and landfast ice, 3. Maintenance of net greenhouse gas uptake in the permafrost domain, 4. Recovery of permafrost and a shallow active layer, and 5. Preservation of human cultural activities and infrastructure. Panel C depicts: 6. Expansion of fossil fuel extraction and marine navigation, 7. Disruption of food webs, migrations, and biological communities on sea and land, 8. Accelerated coastal erosion, aquatic and marine primary productivity, ocean acidification, and erosion of terrestrial material, including pollutants, 9. Transition to net release of greenhouse gases (CH_4, N_2O, and CO_2), 10. Extensive permafrost degradation, including active-layer thickening and lake formation and draining, 11. Intensifying terrestrial disturbances including wildfire, hydrological extremes, thermokarst, vegetation shifts, and invasive species, 12. Profound disruption of human culture and infrastructure.

(**Table 1**). In this paper, we review permafrost climate responses with a focus on mitigation. The sections below highlight how climate change and other human disturbances are affecting the physical, biological, and social fabric of the permafrost domain.

These examples are not comprehensive, and we remind all readers that these regions are composed of diverse ecosystems and peoples with unique histories and ecological contexts (Jorgenson et al., 2013; Chapin, 2020; Tank et al., 2020; Turetsky et al., 2020; Arctic Council, 2022).

Unstable Footing: Terrestrial Permafrost Degradation

Permanently frozen ground or permafrost has developed in cold regions primarily in the Northern Hemisphere (**Figure 1**). The formation and degradation of permafrost depends on complex interactions between local climate and ecosystem characteristics, especially vegetation, water, and glacial history (Shur and Jorgenson, 2007; Lindgren et al., 2018; Loranty et al., 2018). Because of unique soil processes, the permafrost domain has accumulated much of the Earth's freshwater, carbon, nitrogen, phosphorus, and pollutants such as mercury transported from lower latitudes by the atmosphere and rivers (Fisher et al., 2012; Hugelius et al., 2014; Strauss et al., 2017; Malone et al., 2018; Schuster et al., 2018; Abbott et al., 2019; Voigt et al., 2020). For example, cold and waterlogged soils slow microbial decomposition, and periglacial processes can incorporate materials that are produced or deposited on the surface much deeper in the soil than in other regions (Lindgren et al., 2018; FAO, 2021; Finger and Rekvig, 2022).

Soils in the permafrost domain are warming worldwide (Biskaborn et al., 2019; Neumann et al., 2019; Miner et al., 2021; Smith et al., 2022) because of higher air temperature, vegetation shifts, loss of snow and ice cover, surface disturbances, and intensification of the hydrological cycle (Rawlins et al., 2010; Stevens and Latimer, 2015; Forbes et al., 2016; Egelkraut et al., 2018; Loranty et al., 2018; Kropp et al., 2020). Deeper and longer thaw stimulates microbial decomposition—the main driver of GHG release from the permafrost domain (Treat et al., 2015; Schädel et al., 2016; Natali et al., 2019; Voigt et al., 2020; Treharne et al., 2022). Nutrients, trace elements, and pollutants are also released during soil warming, affecting plant growth, microbial activity, and human health (Keuper et al., 2012; Chen et al., 2018; Hewitt et al., 2018; Carey et al., 2019; UNEP, 2019; Mu et al., 2020b; Yang et al., 2021; Basu et al., 2022). While increased nutrient availability and CO_2 fertilization have long been predicted to enhance plant uptake of atmospheric CO_2, observed trends of primary productivity in the permafrost domain have been mixed because of vegetation shifts, droughts, and other disturbances (Forbes et al., 2010; Hayes et al., 2011; Abbott et al., 2016b; McGuire et al., 2018; Rocha et al., 2018; Myers-Smith et al., 2020; Bruhwiler et al., 2021; Mack et al., 2021; Zhao et al., 2021; Vitali et al., 2022).

Terrestrial disturbances in the permafrost domain are intensifying, including wildfire, surface subsidence (*thermokarst*), and direct human disturbance from resource extraction, grazing, and infrastructure. Lengthening dry periods, vegetation shifts, and more lightning are increasing Boreal and Arctic wildfire, with effects on local habitat, air quality, and regional carbon and nutrient cycles (Masrur et al., 2018; Box et al., 2019; Rodríguez-Cardona et al., 2020; Abbott et al., 2021b; Chen et al., 2021; Mack et al., 2021). In addition to directly producing CO_2 and CH_4 during combustion, wildfires

TABLE 1 | Clarifying common misconceptions about permafrost-climate interactions.

Misconception	Correction
The time bomb. The fuse is already lit, and massive meltdown and greenhouse gas release are inevitable within a few years or decades. Abrupt methane release from hydrates, craters, and lakes has been triggered and is now unstoppable.	This view conflicts with modern and paleo observations and modeling, which demonstrate that permafrost feedbacks depend on the degree and duration of warming (i.e., lower human emissions = weaker permafrost climate feedbacks). Because surprising events make evocative headlines (e.g., bubbling methane off the coast, exploding tundra craters, and zombie wildfires), this time bomb misconception is common with the public.
Hakuna matata. Permafrost may release some greenhouse gases someday, but not enough to worry about. The system has so much inertia, it will take centuries before major changes occur, and uptake from plants will offset any release, making permafrost-climate interactions a safety net.	This view does not align with evidence showing permafrost domain sensitivity to climate change. Sea ice and snow cover have plummeted, storms have intensified, soils and coastlines are eroding, and many areas may have already transitioned to net greenhouse gas sources. These changes are harming people and the ecosystems that support them. Permafrost emissions are already similar in magnitude to Japan's. Because policy discussions often focus on emissions by or before 2100, this "no worries" misconception is common in climate policy circles.
Nothing but carbon. Permafrost is best understood as a pile of greenhouse gas precursors. Much like a coal deposit, we just need to make sure the carbon stays in the ground, and everything will be fine.	This view neglects the cultural and habitat importance of permafrost, the dynamic nature of carbon stocks and fluxes, and crucial interactions between carbon, nutrients, water, and disturbance. Unlike a concentrated fossil fuel deposit, permafrost organic matter is distributed across a tenth of the globe, most of it within a few meters of the surface. Human infrastructure, wildlife habitat, climate, and greenhouse gas fluxes are in a delicate and dynamic dance.
Miracle cures. If warming continues, we have multiple tools to protect permafrost habitat and control global climate feedbacks. We can plant trees, distribute ping pong balls on the Arctic Ocean, cultivate peat, inject aerosols into the atmosphere, and reintroduce megafauna, like steppe bison and mammoths, to increase soil carbon.	This perspective underestimates the magnitude of human emissions and the size of the permafrost domain. It also overestimates our technical capabilities and ignores the unintended consequences inherent in unproven ecological manipulations of this size. While local and regional-scale efforts to reduce GHG emissions have intrinsic and extrinsic value, there are no known scalable permafrost "climate hacks" that will miraculously allow us to continue burning fossil fuels while preserving permafrost globally. Rapidly reducing human emissions and drawing down atmospheric greenhouse gases are the only proven ways to protect the permafrost domain.

warm soil through loss of insulating vegetation and albedo changes. This can stimulate organic matter decomposition and hydrological export for decades after the wildfire (Grosse et al., 2011; Rocha and Shaver, 2011; Carey et al., 2019; Meredith et al., 2019; Abbott et al., 2021b; Bruhwiler et al., 2021). Permafrost wildfires are expanding northward and even burning through the winter (Holloway et al., 2020; McCarty et al., 2020; Scholten et al., 2021; Veraverbeke et al., 2021; Talucci et al., 2022).

In areas with ground ice, soil warming often triggers abrupt surface collapse, mass wasting, and coastal erosion (Kokelj and Jorgenson, 2013; Olefeldt et al., 2016; Grotheer et al., 2020; Angelopoulos et al., 2021). These thermokarst processes have a wide range of consequences depending on landscape position and soil characteristics (Mu et al., 2020a; Turetsky et al., 2020; Yang et al., 2021), including soil warming, GHG release or uptake, and delivery of sediment and solutes to aquatic ecosystems (Anthony et al., 2014; Abbott et al., 2015; Farquharson et al., 2019; Kokelj et al., 2021; Wologo et al., 2021; Yang et al., 2021). Subsidence can result in complex changes in soil moisture, affecting the type and amount of GHGs produced, further complicating estimates of permafrost climate feedbacks (Lupascu et al., 2013; Lawrence et al., 2015; Boike et al., 2016; Schuur et al., 2022). Approximately 20% of the northern permafrost region is vulnerable to thermokarst formation, which can trigger rapid GHG release and damage human infrastructure and wildlife habitat (Olefeldt et al., 2016; Hjort et al., 2018; Turetsky et al., 2020; Gao et al., 2021).

While the permafrost domain generally has low human population density, direct human impacts are extensive and growing. Fossil fuel extraction, logging, peat harvesting, and construction of roads, power lines, and buildings can cause soil warming or collapse by disturbing vegetation and modifying surface conditions, including moisture and albedo (Van Seters and Price, 2001; Kreutzweiser et al., 2008; Lamers et al., 2015; Bartsch et al., 2021; FAO, 2021; Maslakov et al., 2021). Some human activities, such as grazing, can cool or warm soils depending on the intensity of the disturbance and local ecosystem attributes including soil structure and vegetation community (Egelkraut et al., 2018; Beer et al., 2020; FAO, 2021). Many of these large-scale human activities are driven by demand for energy, fiber, and tourism from outside the permafrost domain, adding another layer to the environmental injustice of climate change (Johnson, 2010; Chapin, 2021).

Troubled Waters: Hydrochemical Disruption From Streams to Seas

Though terrestrial, freshwater, and marine environments are often considered separately, they are closely coupled climatically, biogeochemically, and culturally (Bhatt et al., 2010; Kling, 2010; Chapin et al., 2013; Forbes et al., 2016; MacDonald et al., 2021). This is especially true in the permafrost domain, where the ground is often held up by frozen water, extensive freshwater networks blur boundaries, and sea ice regulates exchange of energy and material among land, sea, and atmosphere (Campeau et al., 2019; Harms et al., 2019; IPCC, 2019; Shogren et al., 2021). Indeed, much of the marine habitat in the Arctic Ocean still carries thermal and biogeochemical legacies from when it was terrestrial during the Last Glacial Maximum (**Figure 1A**) (Frederick and Buffett, 2016; Overduin et al., 2019; Angelopoulos et al., 2020; Sayedi et al., 2020). Consequently, terrestrial and marine disturbances are strongly interlinked. For example, the release of sediment, organic matter, and pollutants from degrading permafrost can alter aquatic food webs, influence migrations of marine animals, and expose human communities to biomagnified pollutants (AMAP, 2017; UNEP, 2019). Likewise, loss of sea ice increases atmospheric moisture and energy availability, driving shifts in terrestrial vegetation and likelihood of extreme precipitation events (Bhatt et al., 2010; Forbes et al., 2016).

The Arctic Ocean and surrounding seas (referred to hereafter simply as the *Arctic Ocean*) play pivotal roles in global climate, ocean circulation, marine and terrestrial biodiversity, and international politics and commerce (Steinacher et al., 2009; Carmack et al., 2016; Chou et al., 2021; Arctic Council, 2022). Like in terrestrial permafrost regions, many changes in the Arctic Ocean are occurring decades faster than predicted (Steinacher et al., 2009; Boers and Rypdal, 2021; Parkinson and DiGirolamo, 2021). Sea ice extent and thickness have plummeted, with summer ice expected to disappear mid-century (IPCC, 2019). Freshwater inputs have increased because of glacial and icesheet melt and climbing river discharge (Bamber et al., 2018; King et al., 2020; Feng et al., 2021). At the same time, terrestrial permafrost degradation and pollution from outside the permafrost domain are substantially altering the delivery of carbon, nutrients, sediment, and pollutants via coastal collapse, river discharge, groundwater flux, and atmospheric transport (Fisher et al., 2012; Tank et al., 2016; Toohey et al., 2016; Fritz et al., 2017; Drake et al., 2018; Connolly et al., 2020; Wologo et al., 2021; Mann et al., 2022).

Coastal erosion and riverine material fluxes are changing particularly rapidly (Fritz et al., 2017; Tank et al., 2020). Coastal collapse has been supercharged by three factors: permafrost degradation, increased wave action from sea ice loss, and intrusions of saltwater (Jones et al., 2009; Lantuit et al., 2012; Berry et al., 2021; Guimond et al., 2021). Coastal erosion rates now exceed $20\,\mathrm{m\,yr^{-1}}$ in some areas, though differences in local conditions create high spatial variability (Lantuit et al., 2012; Günther et al., 2015; Fritz et al., 2017). Changes in riverine transport are being caused by hydrological intensification, thickening of the seasonally-thawed active layer, widespread thermokarst formation, and changes in plant uptake of water and nutrients (Toohey et al., 2016; Treat et al., 2016; Carey et al., 2019, 2020; Shogren et al., 2020; Tank et al., 2020). Interacting disturbances, such as wildfire, thermokarst formation, and extreme hydrological events can deliver large pulses of material to river networks and Arctic estuaries (Holmes et al., 2012; St. Pierre et al., 2018; Rodríguez-Cardona et al., 2020; Abbott et al., 2021b). For example, in the western Canadian Arctic, mass wasting along fluvial networks has increased two orders of magnitude from 1986–2018, creating sedimentary deposits that will cascade through rivers and lakes to the Arctic Ocean for decades to millennia (Kokelj et al., 2021). Understanding and preventing changes in water chemistry and river discharge are particularly important for the Tibetan Plateau, which provides drinking and agricultural water for 1.4 billion people (Yao et al., 2018; Mu et al., 2020b; Gao et al., 2021).

Riverine and coastal erosion is also releasing trace metals and semi-volatile contaminants from permafrost and active-layer soils (Loiko et al., 2017; Schuster et al., 2018; St. Pierre et al., 2018; Perryman et al., 2020; Basu et al., 2022). These toxic materials include mercury, organochlorines, PAHs, and other compounds that accumulate naturally or from human pollution such as coal combustion and mining (Fisher et al., 2012; AMAP, 2021). The permafrost domain's aquatic environments are especially vulnerable to these global contaminants largely due to efficient transport pathways and bio-accumulating and biomagnifying processes (Fahnestock et al., 2019). Mercury is of special concern because one of its neurotoxic forms, methylmercury, accumulates in food webs and is found at elevated levels in wildlife and human populations across the circumpolar north (AMAP, 2011; Basu et al., 2022). Because of its strong influence on redox state and bioavailability of metals, the release of terrestrial organic matter may also foster the production and transport of methylmercury in aquatic environments (Stern et al., 2012; Abbott et al., 2016a; Fahnestock et al., 2019).

In addition to altered material flux from terrestrial environments, climate change is affecting the Arctic Ocean directly. The characteristics of the Arctic Ocean make it highly vulnerable to ocean acidification, "the other CO_2 problem" (Bates and Mathis, 2009; Doney et al., 2009; AMAP, 2017). Acidic conditions decrease the availability of calcium carbonate, disrupting marine primary and secondary production (Yamamoto-Kawai et al., 2009; Denman et al., 2011). Arctic Ocean biogeochemistry is dominated by land-derived runoff, receiving ~ 11% of global river runoff while constituting just 1% of ocean volume (McClelland et al., 2012). Consequently, the Arctic Ocean's cold and poorly-buffered surface waters absorb large quantities of CO_2 (Bates and Mathis, 2009; Bruhwiler et al., 2021). The decomposition of terrestrial organic matter adds more CO_2, further decreasing pH (Alling et al., 2012; Semiletov et al., 2016; Tanski et al., 2021). Strong vertical stratification and sea ice prevent mixing within the water column and exchange with the atmosphere, resulting in rapid acidification in some of the most vulnerable compartments of the Arctic Ocean (Bates and Mathis, 2009; Yamamoto-Kawai et al., 2009; Vonk et al., 2012; Ouyang et al., 2020). The combined effects of rising CO_2, increased meltwater inputs, and changes in circulation could push calcium carbonate below critical saturation thresholds in the Arctic Ocean's surface water by the mid-21st Century (Steinacher et al., 2009; Denman et al., 2011). In combination with increasing thermal stresses, this could trigger major breakdowns in planktonic and benthic food webs (Yamamoto-Kawai et al., 2009; Denman et al., 2011; Arrigo et al., 2020). For example, the combination of increased light availability from sea ice loss and changes in water and nutrient delivery from terrestrial ecosystems is estimated to have increased primary productivity in the Arctic Ocean by roughly 60% over the last 20 years (Lewis et al., 2020; Terhaar et al., 2021). This state change could cause the loss of ecological niches and biodiversity in Arctic food webs.

Predicting and Shaping Permafrost Futures

Given the complexity of the permafrost domain and the unprecedented speed of climate change, we do not know the specific timeline and severity of disruption to its peoples, biodiversity, and biogeochemistry (Proverbs et al., 2020; Bruhwiler et al., 2021; Canadell et al., 2021; Fewster et al., 2022; Mann et al., 2022; Versen et al., 2022). For example, the most comprehensive permafrost model intercomparison project (MIP) of carbon balance estimated a range of ~600 Gt of carbon release to ~200 Gt of carbon uptake by the year 2300 (McGuire et al., 2018). Though the divergence of model outputs is clearly problematic, the multi-model mean of this study has become the default reference for comparison (Turetsky et al., 2020; de Vrese and Brovkin, 2021; Natali et al., 2021). These models were state-of-the art seven to 10 years ago, but there have been considerable advances in permafrost domain modeling since then (Randers and Goluke, 2020; Shu et al., 2020; Smith et al., 2021; Wiltshire et al., 2021; Chadburn et al., 2022). This emphasizes the larger problem of the continued exclusion of permafrost in Earth system models. Only 4 of 11 CMIP6 models used for IPCC AR6 included permafrost (IPCC, 2019, 2021), and only two of the 18 models in the Zero Emissions Commitment model intercomparison included permafrost dynamics (MacDougall, 2021).

Because the stakes of environmental change in the permafrost domain are so high for human and nonhuman permafrost communities, we need to use all available tools for monitoring and prediction. For example, recognizing these shortcomings of Earth system models, the IPCC AR6 WG1 estimated permafrost climate feedbacks using a range of different methods, including empirically based studies (Canadell et al., 2021). In research, management, and policymaking, we need to fully integrate traditional ecological knowledge, empirical and model-based evidence, expert assessments, and paleo studies considering the full range of socioecological consequences (Kimmerer, 2002; Sayedi et al., 2020; Chapin, 2021; Arctic Council, 2022). Specifically, we need to consider disruptions and sources of resilience that cascade across ecosystem boundaries (e.g., terrestrial, freshwater, marine) and ecological dimensions (e.g., human wellbeing, biosphere integrity, and biogeochemical cycles). Identified research and management priorities go far beyond questions of carbon balance, including: Arctic Ocean circulation, marine and coastal habitat, destabilization of organic matter and methane clathrates on the continental shelves, thermokarst formation, fire-induced thaw, nutrient interactions, peatland dynamics, and socioecological adaptation and resilience (Lewis et al., 2020; Voigt et al., 2020; FAO, 2021; Finger and Rekvig, 2022; Mettiäinen et al., 2022).

What can we do?

Persistent uncertainty about permafrost processes does not limit our ability to act now to protect the permafrost domain. Across traditional, modeled, and empirical approaches, there is consensus that the timing and degree of damage to the permafrost domain are directly associated with the amount of human-caused warming (Canadell et al., 2021; Abbott B. W., 2022; Cheng et al., 2022; Fewster et al., 2022). The question then becomes, how can we most effectively reduce anthropogenic climate change?

In very general terms, there are three non-exclusive approaches to stopping climate change: 1) Reduce human GHG emissions, 2) Protect ecosystems to sustain natural GHG sinks, and 3) Attempt to control the Earth's energy balance through geoengineering. The first two approaches are feasible, cost-effective, and come with a wide array of co-benefits (Foley et al., 2011; Breyer et al., 2021; Chapin et al., 2022). For example, eliminating fossil fuel burning could prevent 10.2 million premature deaths each year and add US$10 trillion annually in economic benefits from improved air quality (Errigo et al., 2020; Shindell et al., 2021; Vohra et al., 2021; Abbott B., 2022). Likewise, collaboratively expanding conservation of intact ecosystems enhances biosphere integrity and can restore rights of Indigenous and immigrant peoples of the permafrost domain (Steffen et al., 2018; Watson et al., 2018; Díaz et al., 2019; Bergstrom et al., 2021; Chapin et al., 2022). Unfortunately, the third approach (geoengineering) is both less proven and more prone to unintended consequences (Lawrence et al., 2018; Zarnetske et al., 2021; Mettiäinen et al., 2022; Versen et al., 2022).

A wide suite of geoengineering interventions have been proposed in the permafrost domain, including solar radiation management (SRM), ocean brightening, artificial sea-ice creation, ocean fertilization, biomass energy with carbon capture and storage (BECCS), and biomanipulations such as tree planting and herbivore introductions (Olson, 2012; Harper et al., 2018; Whyte, 2018; Zampieri and Goessling, 2019; Beer et al., 2020; Chen et al., 2020; Zarnetske et al., 2021; Mettiäinen et al., 2022; Versen et al., 2022). While continued research into some of these interventions is merited, all have serious side effects and known ethical and practical limitations (Tuana et al., 2012; Lawrence et al., 2018; Mettiäinen et al., 2022). For example, SRM could theoretically reduce temperatures enough to protect a portion of the permafrost domain (Chen et al., 2020). However, this would not solve acidification of the Arctic Ocean and would very likely disrupt global agriculture while exacerbating the Arctic ozone hole (Tilmes et al., 2008; Proctor et al., 2018; Zarnetske et al., 2021). Likewise, converting portions of the Boreal forest for BECCS could decrease local ecosystem carbon storage while producing pollution that would harm public health and create substantial regional warming from black and brown carbon deposition (Hanssen et al., 2020; Calì Quaglia et al., 2022; Yue et al., 2022). Additionally, many of these proposed solutions may be ineffective or counterproductive in the new conditions created by anthropogenic climate change. For example, the survival of large herds of herbivores could be negatively affected by shifts in forage and extreme weather events (Forbes et al., 2016; Zarnetske et al., 2021), and carbon uptake from tree planting can be erased by temperature-induced mass mortality and an intensifying wildfire regime

(Hammond et al., 2022; Talucci et al., 2022). Even if these interventions achieved their climate goals, they would threaten more than half of remaining intact ecosystems globally (Watson et al., 2018; Díaz et al., 2019).

We conclude that rapid reduction of fossil fuel emissions and empowerment of local communities are needed to conserve permafrost ecosystems. While many scientific questions remain about permafrost-climate complexities, we know that the faster the drawdown of atmospheric GHGs, the more of the permafrost domain will be preserved (Canadell et al., 2021; Abbott B. W., 2022). Because of the permafrost domain's immensity and momentum (Schuur et al., 2015; Lindgren et al., 2018; Biskaborn et al., 2019; Sayedi et al., 2020; de Vrese and Brovkin, 2021), the choices we make over the next decade regarding GHG emissions could either open pathways towards recovery and conservation or lock us into a future of loss and degradation (**Figure 1**) (King et al., 2020; Ritchie et al., 2021; Abbott B., 2022). Consequently, the future of the permafrost domain depends on energy choices made far beyond its borders.

Thankfully, recent breakthroughs in renewable energy production, transmission, and storage now allow much faster decarbonization than previously believed possible (Bogdanov et al., 2021; Victoria et al., 2021; Jacobson et al., 2022). The costs of solar photovoltaics and wind turbine have plummeted 91 and 71%, respectively since 2009, now providing the cheapest and cleanest electricity ever available to humankind (Abbott et al., 2021a; Breyer et al., 2021; Abbott B., 2022). Global markets have already responded, with renewables constituting 90% of all new electricity capacity built in 2021 (IEA, 2021a) and 95% of all projected growth through 2025 (IEA, 2021b). With doubling periods of 3.7 years for wind and 1.9 years for solar, renewables could meet global electricity demand within 10 years and all primary energy demand within 25 (Rockström et al., 2017; Haegel et al., 2019; Abbott et al., 2021a; Bogdanov et al., 2021; Abbott B., 2022). Mature technologies now allow electrification of nearly the entire economy (transportation, manufacturing, agriculture, etc.), with developing technologies on track to allow full decarbonization before 2040 (Breyer et al., 2021; Jacobson et al., 2022). If the global community commits to sustaining this ongoing transition, the clean and abundant energy will also bring down costs of direct air carbon capture and storage (DACCS), one of the few scalable and sustainable geoengineering approaches (Breyer et al., 2020). The combination of abrupt global decarbonization and renewable DACCS could enable a return to Holocene-like conditions by the end of the century (Breyer et al., 2021; Abbott B., 2022).

Now that the technology and economics for rapid decarbonization and atmospheric drawdown of CO_2 are in place, meeting our moral responsibility to restore the Earth's climate is in reach. Rather than aiming for 1.5–2 °C of warming—a level of change that would cause radical transformation and widespread destruction throughout the permafrost domain (Farquharson et al., 2019; King et al., 2020; Ritchie et al., 2021)—we must aim for restoring Holocene-like climate conditions by stopping fossil fuel burning while supporting natural GHG sinks and developing negative emissions technologies (Breyer et al., 2020; Abbott B., 2022).

While pursuing abrupt GHG drawdown at global scales, we must support and empower communities in the permafrost domain who are adapting to unprecedented environmental and economic changes, and who are essential to the sustainable conservation of these ecosystems (Díaz et al., 2019; Proverbs et al., 2020; Chapin et al., 2022; Mettiäinen et al., 2022). For both practical and ethical reasons, we need to follow the guidance of the Indigenous and other local peoples with the most at stake and the deepest knowledge of the complex ecological responses across the permafrost domain (Kimmerer, 2002; Proverbs et al., 2020; Chapin, 2021). Greater recognition of forums such as the Arctic Council and Inuit Circumpolar Council could contribute to this goal (Johnson, 2010; Kristoffersen and Langhelle, 2017; Arctic Council, 2022; ICC, 2022; Koivurova and Smieszek, 2022). We call on people everywhere to share and promote the empowering and evidence-based assessment that we have the tools to reverse climate change and protect the irreplaceable permafrost domain.

AUTHOR CONTRIBUTIONS

BA and LG conceived of the paper concept. The entire co-author team collaboratively wrote and revised the manuscript.

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