Organic matter storage and vulnerability in the permafrost domain

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Abstract

This chapter synthesizes information about the storage and vulnerability of organic matter in permafrost. The permafrost region is rapidly warming, leading to degradation and release of carbon. Permafrost holds a vast amount of organic carbon (~1460–1600 gigatons ($\mathrm{Gt} = 10^9\ t = 10^{12}$ kg) on land, and in total more than 4300 Gt (including organic carbon in subsea permafrost), making the permafrost domain the Earth's largest terrestrial carbon pool. The thawing of permafrost also affects ecosystem types and greenhouse gas emissions. Projections suggest that by 2100, the Arctic could release between 55 and 232 Gt carbon of CO_2-equivalent, highlighting the potential to release carbon in amounts similar to that from a large industrial nation. While the possibility of a sudden release of greenhouse gases is not confirmed yet, permafrost destabilization increases the likelihood of the Arctic becoming a continuous carbon source, crucial to be included in climate mitigation considerations.

Keywords

Arctic warming; Carbon stocks; Emissions; Greenhouses gases; Permafrost; Thaw; Thermokarst

Glossary

Arctic warming The increase in average temperatures in the Arctic region, which is occurring at a faster rate than the global average.
Cryoturbation The process of mixing and displacing soil and sediment particles due to freeze–thaw cycles in permafrost regions.
Lowland permafrost Permafrost existing in high latitudes and outside of alpine areas
Mountain permafrost (also alpine permafrost) Permafrost existing at high altitudes, also occurring in middle and low latitudes.
Organic matter Material derived from living organisms, such as plants and animals, which contains carbon and other compounds.
Thermokarst Process: melting of excess ground ice and subsequent thaw settlement, often caused by a water body (thermokarst lake); Landform: topography resulting from the melting of excess ground ice and subsequent thaw settlement. Thermokarst terrain is so named because of its superficial resemblance to the karst topography typical of limestone regions.
Vulnerability The degree to which something is susceptible to harm or damage.

Key points

- The permafrost domain is the largest terrestrial carbon pool on Earth.
- Permafrost thaw has a carbon release potential in the same order of magnitude as that from a large industrial nation.
- Permafrost carbon release is dominated by CO_2, but will involve increasing amounts of CH_4 with time.
- The vast majority of the permafrost carbon pool is located in the northern high latitudes where the temperature increase is significantly higher (up to 4-times) than the global average.

Introduction

Under cold and wet conditions a hidden repository of organic matter that has accumulated over millennia underlies the northern permafrost regions (Hugelius et al., 2014; Mishra et al., 2021; Palmtag et al., 2022; Miesner et al., 2023), and the elevated Tibetan Plateau (Ding et al., 2016). This permafrost reservoir of organic matter, primarily derived from the remnants of ancient plants, animals, and microorganisms, has come under the scientific spotlight through studies since the early 2000s and information about it has been synthesized by several recent reports (e.g., IPCC, 2019) and high-level reviews (e.g., Schuur et al. (2022), Strauss et al. (2021a). In this chapter, we summarize the state of knowledge on permafrost soil organic matter and its key components—organic carbon and nitrogen.

Permafrost, a geological phenomenon marked by ground temperatures below 0 °C for at least 2 consecutive years, causes the 'freezer effect'—a climate-driven inhibition of microbial decomposition of organic matter. This unique interplay between soil freezing conditions and organic matter accumulation has given rise to extensive deposits of organic-rich soils and deep strata (Hugelius et al., 2014), despite the Arctic's short growing season. As global atmospheric temperatures increase, particularly in northern high latitudes (Rantanen et al., 2022), the preservation of this ancient carbon is increasingly under pressure as the thawing of permafrost occurs by gradual, top-down thaw and also by deep thaw and deep ground collapse (Turetsky et al., 2020). Soil warming and thaw cause increased microbial activity and the decomposition of previously frozen soil organic matter, which leads to the production of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) (Schuur et al., 2022) as well as other non-carbon-based greenhouse gases such as nitrous oxide (N_2O), which are all potent contributors to global climate change (Voigt et al., 2020). While the Arctic may appear distant and isolated, these environmental shifts unfolding in the remote permafrost 'freezer box' have far-reaching implications for societies and ecosystems across the globe as permafrost is lost and the vast organic matter pool is becoming accessible for microbial decomposition with rising temperatures.

Recent records document that mean annual air temperatures in the Arctic are rising at a rate 2–4 times faster than the global average (Rantanen et al., 2022). In step with a warming climate, changes in the extent and temperature of permafrost have been observed in boreholes at depths of 10–20 m, underscoring the profound warming trend observed in the northern circumpolar permafrost region over the past decade (Biskaborn et al., 2019; Smith et al., 2022). On top of this warming trend, changes in rainfall and wildfire are also leading to accelerated rates of permafrost thaw. This ongoing transformation hints at the new dynamic nature of permafrost landscapes. Permafrost thaw often is not a gradual process but rather accelerated by locally abrupt responses to ongoing climate warming or disturbances, causing challenges for adaptation (Grosse et al., 2011). Moreover, drastic reductions across all of Earth's cryosphere elements—comprising snow, ice, and permafrost—intensify climatic change through intricate feedback mechanisms. The permafrost–climate feedback amplifies climate warming further by releasing previously frozen carbon into the atmosphere as greenhouse gases that further warm the atmosphere. Even a fraction of the frozen organic matter released as greenhouse gases can accelerate global climate warming, setting in motion this self-reinforcing process that affects polar and mountainous regions alike (Schuur et al., 2008).

Model projections suggest a continued thaw on a global scale, driven by factors like rising land surface and ocean temperatures and the extension of ice-free seasons in the Arctic Ocean (IPCC, 2019). These changes carry inevitable consequences, from altering river runoff to exacerbating local hazards such as surface subsidence, thaw slumps and coastal erosion as well as the above mentioned risk of releasing additional carbon into the atmosphere (Treharne et al., 2022). By the end of the 21st century, the fate of permafrost organic matter depends on emission scenarios. High-emission scenarios may result in substantial carbon release, primarily as CO_2, CH_4, as well as N_2O with the potential to exacerbate climate change. As these permafrost–climate feedbacks await integration into climate projections, they pose challenges to current climate policy objectives, because some essential processes are not yet accounted for in global models, such as thermokarst (Nitzbon et al., 2020; Turetsky et al., 2020; Miner et al., 2022) and intricate ecological interactions (Keuper et al., 2020), which may further amplify these emissions.

Unlike the visible changes observed in sea ice, glaciers, and ice sheets, the transformation of subsurface permafrost eludes global-scale satellite remote sensing. Consequently, our understanding remains fragmented, even in the face of record-setting warming witnessed by the permafrost borehole-monitoring networks (Biskaborn et al., 2019). In this synthesis, we look into the (1) **processes** leading to the sequestration of organic matter in permafrost and the (2) **quantity** of the frozen and unfrozen organic matter reservoir within permafrost regions. We also consider the (3) **intricate dynamics of organic matter in degrading permafrost**, summarizing the latest knowledge about the potential consequences for the global carbon cycle and its complex feedback loops with climate change.

Organic matter sequestration processes

In cold-region (permafrost) landscapes, organic matter accumulates as a result of several key factors. Firstly, permafrost systems are characterized by low rates of organic carbon input from plants. But because losses from decomposition are even lower, it results in net carbon accumulation. The question of 'where does the permafrost carbon come from?' leads us to explore the mechanisms responsible for the storage of carbon within these frozen landscapes, which are mainly driven by the landscapes topography, vegetation, hydrology and, of course, the permafrost conditions (Fig. 1). All of this, but especially the permafrost, is influenced by the modern climate, but also by the legacy from past climatic conditions (Jones et al., 2023) (Fig. 1).

Organic matter inputs: The beginning of the story

The journey of permafrost organic matter storage begins with its inputs, primarily derived from the remnants of ancient plants, insects, animals, and microorganisms. Cold and wet (anoxic) conditions, typical for many permafrost regions, limit litter decomposition. In combination with continued accumulation of organic matter and soil mixing processes (e.g., cryoturbation), this has led to the accumulation of large stocks in frozen ground over multi-millennial timescales. This carbon pool has been protected from decomposition by remaining frozen within permafrost but now becomes highly vulnerable because of future climatic warming.

Organic matter stabilization: Preserving organic matter for millennia

Organic matter stabilization mechanisms play an essential role in sequestering organic matter. These include firstly permafrost aggradation. As permafrost layers grow over thousands of years, they effectively lock organic matter within the frozen permafrost, shielding it from decomposition. Besides being frozen, organic matter can be protected by anoxic conditions and by mineral–organic interactions (Opfergelt, 2020).

Focusing on the freezing, the term 'freeze–locking' encapsulates the essence of permafrost organic matter preservation. The three above mentioned key stabilization mechanisms, including low temperature, anoxic conditions, and mineral protection, are boosted by three key stabilization processes:

(1) Cryoturbation: the innumerable cycles of freeze and thaw cause soil movement, transporting surface organic matter to deeper layers (see article on Cryoturbation structures). This leads to a relocation of fresh surface organic matter deeper into the subsoil 'freezer.' Over time, this cryoturbated organic matter becomes an integral part of the permafrost, contributing to substantial organic matter stocks. Cryoturbation is a key process leading to fast downward organic matter relocation and thus the large organic matter stocks in the Arctic soil sub-order Turbels (Table 1).

(2) Peat accumulation: the formation of peat layers, with or without permafrost, contributes to the long-term organic matter storage in both Histels and Histosols types of soils (Table 1). While permafrost peatlands lose carbon to the atmosphere when they thaw, there is also potential for increased rates of peat accumulation mostly due to changing vegetation communities as well as new peatland formation (Turetsky et al., 2020). The latter would require additional areas for suitable peat formation, such as thermokarst bog expansion, drained thermokarst lakes (Walter Anthony et al., 2014) or newly exposed, poorly drained surfaces (e.g., areas of coastal uplift after glacial recession (Treat et al., 2019), or other changes in environmental conditions that promote widespread peat formation. However, given that the formation of peat is a slow process compared to climate warming rates, current projections suggest that losses of C from thawing permafrost in peatlands will likely be larger than the gains for several centuries (Hugelius et al., 2020).

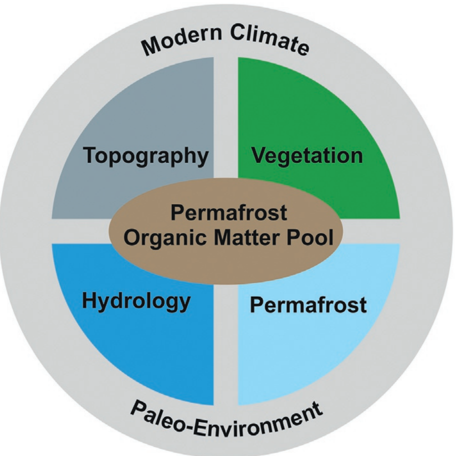

Fig. 1 Major influencing factors of the permafrost organic matter pool. All of these factors not only influence the permafrost organic matter pool, but also interact with each other.

Table 1 Estimates for different components of the permafrost region soil organic C stock.

Unit	*Depth (m)*	*Region*	*Gt C*	*Reference*
Turbels	0–3	Terrestrial, lowland permafrost, Northern Hemisphere (NH)	476	Hugelius et al. (2014)
Orthels	0–3	Terrestrial, lowland permafrost (NH)	98	Hugelius et al. (2014)
Histels	0–3	Terrestrial, lowland permafrost (NH)	153	Hugelius et al. (2014)
Histosols	0–3	Terrestrial, lowland permafrost (NH)	149	Hugelius et al. (2014)
Non-Gelisols, mineral	0–3	Terrestrial, lowland permafrost (NH)	158	Hugelius et al. (2014)
Permafrost deep peatlands	>3	Terrestrial, lowland permafrost (NH)	32	Hugelius et al. (2020)
Deltaic alluvium	>3–54	Terrestrial, lowland permafrost (NH)	91	Hugelius et al. (2014)
Yedoma region[a]	>3–50	Terrestrial, lowland permafrost (NH)	297	Strauss et al. (2017)
Mountain permafrost excluding Tibetan Plateau		Terrestrial, high altitude	47	IPCC (2019)
Tibetan Plateau	0–3	Terrestrial, high altitude	37	Ding et al. (2019)
Subsea permafrost	0–3	Subaquatic	93	Calculated from Miesner et al. (2023) and Sayedi et al. (2020)
Subsea permafrost	3–25	Subaquatic	1217	Calculated from Miesner et al. (2023)
Subsea permafrost	>25	Subaquatic	1512	Calculated from Miesner et al. (2023)
In permafrost, terrestrial[b]		Global	1024	References mentioned above
In permafrost, including subsea		Global	3846	References mentioned above
Total permafrost region, terrestrial		Global	~1538 (1460–1600)	Strauss et al. (2021a) and IPCC (2019)
Total permafrost region, including subsea		Global	4360	Sum of the references mentioned above
Additional in other deep deposits[c]	3–10	Terrestrial, lowland permafrost (NH)	400	Schuur et al. (2015)

[a]Lower boundary of the yedoma region minus the uppermost 3 m causes the difference to Strauss et al. (2017) estimate for full 0–50 m yedoma pool (327 Gt C).
[b]Estimated assuming an active layer depth of 30 cm or more in all Gelisols/High Arctic soils and 46% of the Tibetan Plateau C perennial frozen.
[c]Rough estimate of potential permafrost carbon in regions with additional thick sedimentary overburden. Not included in any calculations yet due to very high uncertainties.

(3) Ongoing deposition: sediments transported by wind, water, and slope processes over geological time scales have buried organic matter in deep deposits across the permafrost regions. Ice-rich yedoma deposition during the Late Pleistocene is a prominent example of this mechanism (Strauss et al., 2017; Strauss et al., 2021b), see article on yedoma). Another example are Arctic deltas, where large quantities of sediments including organic matter are deposited by Arctic rivers in deep permafrost deposits (Hugelius et al., 2014; Overeem et al., 2022). Both, Arctic deltas and yedoma, are deep (>3 m) permafrost C pools that will be affected by a warming permafrost region and abrupt thaw processes affecting deeper C-rich sediments. Regarding Arctic deltas, it is so far unclear how increased river discharge, permafrost thaw in the catchments and a prolonged open-water season will affect biogeochemical processes (and the C sink and C source capacity) of deltaic deposits (Overeem et al., 2022). Solifluction (flow of saturated soil downslope, Fig. 2) can bury surface organic matter in the accumulation zone; but relatively little is known about this mechanism for organic matter preservation. Permafrost organic matter can also be eroded, transported, and sequestered in river, delta, and ocean sediments, although the relative stability and residence time is currently being assessed in different rivers and deltas across the Arctic (Mann et al., 2022).

Organic matter destabilization

Despite permafrost's role as a store of organic matter, permafrost destabilization mechanisms are accelerating as a result of rising ground temperatures. The major mechanisms of organic matter destabilization and mobilization, including deeper thawed layers, are illustrated in Fig. 2. These are active-layer deepening, thermokarst development, riverbank and coastal erosion as well as thaw slumping, forest and tundra fires, and human land use. Beside human-caused fossil fuel burning and climate warming (Abbott et al., 2022), other human activities can destabilize permafrost and release stored carbon back into the atmosphere, reversing the long-term preservation achieved by stabilization mechanisms. All of these mechanisms enable microbes to recycle portions of the formerly frozen carbon pool and re-introduce it into active carbon cycling, leading to microbial decomposition. It can be released and transported in various forms:

- Lateral fluxes of dissolved and particulate organic matter: Carbon can be transported within water and suspended particles, contributing to organic matter exports (McClelland et al., 2016; Mann et al., 2022).
- Gas fluxes: Organic matter can escape into the atmosphere as greenhouse gases (e.g., CO_2, CH_4, and N_2O; Hugelius et al., 2023).

Both kinds of fluxes could also be combined, as the lateral relocated organic matter can also be released into the atmosphere as gas elsewhere.

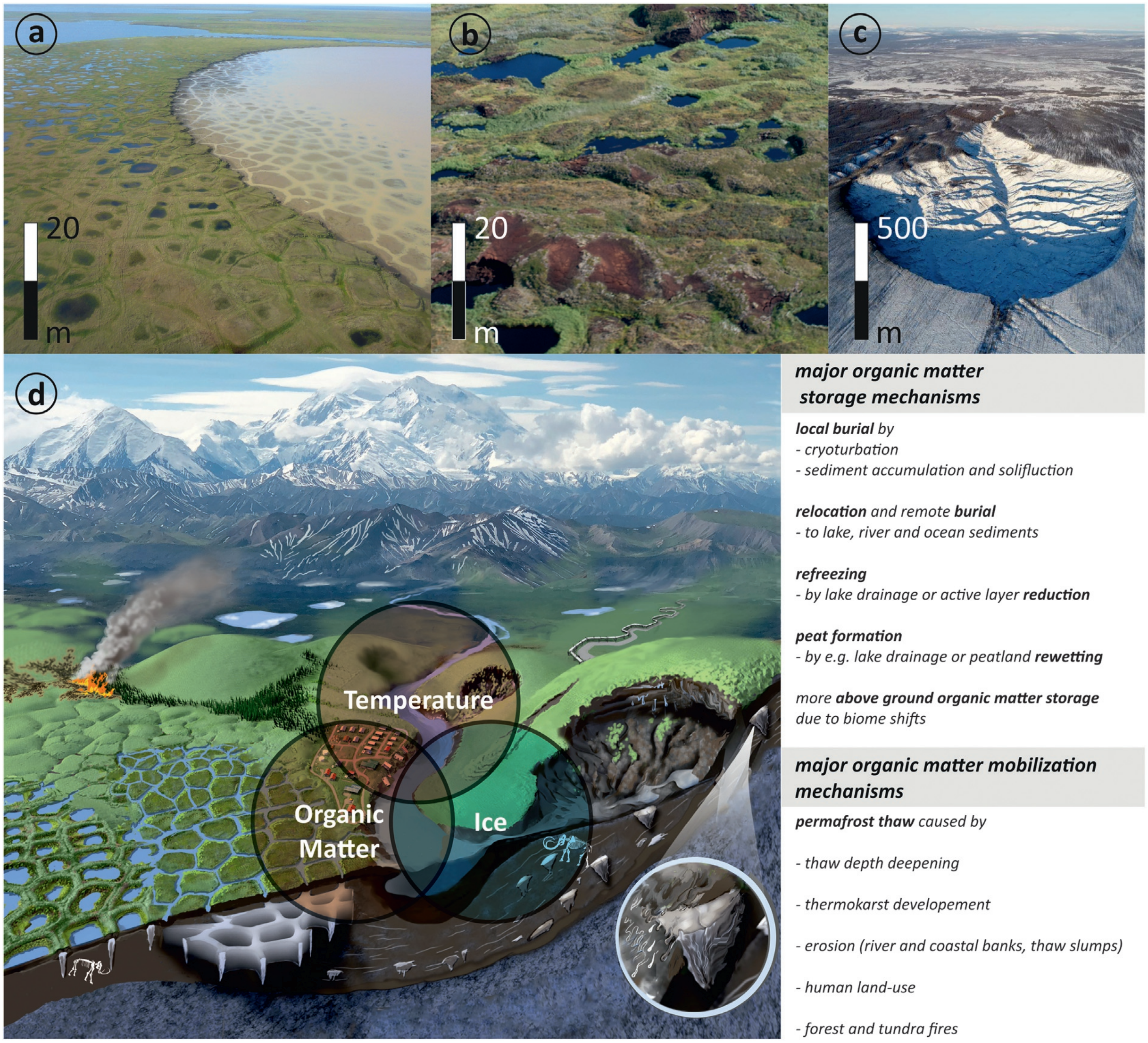

Fig. 2 Permafrost landscape features with a focus on lowland permafrost of the Northern Hemisphere. (A) Thermokarst degradation by lake expansion in northern Alaska. (B) Palsa peatland complex in Tavvavuoma, Sweden. (C) Batagay thaw slump in the boreal zone of Yakutia, Russia. (D) Cartoon of major processes and landscape features with three components (illustrated as overlapping circles) of frozen ground (temperature, ice, and organic matter) that comprise key ecosystem services to people. Temperature (and time) comprise the classical definition of permafrost. The amount of ice determines the structural integrity of frozen ground in the face of permafrost thaw. The amount of organic matter determines the impact on atmospheric composition and climate as the greenhouse gases are released from thawing permafrost (from Schuur et al., 2022, drawn by Victor Leshyk). Images (A) Josefine Lenz, 2018; (B) Matthias Siewert, 2012; and (C) Alexander Kizyakov, 2019. Figure adapted from Strauss J, Abbott B, Hugelius G, Schuur EAG, Treat C, Fuchs M, Schädel C, Ulrich M, et al. (2021a) Permafrost. In: FAO and ITPS (eds.) *Recarbonizing Global Soils—A Technical Manual of Recommended Management Practices*, pp. 127–147. Rome, Italy: Food and Agriculture Organization of the United Nations.

Beside top-down thaw, permafrost can also be destabilized by thermokarst processes. Such processes are characterized by the rapid loss of ground ice, which is the cement that holds permafrost together, especially in ice-rich landscapes such as the yedoma region (see articles on Yedoma and Thermokarst topography). Reduced soil cohesion, volume loss by melting of excess ice, and subsequent and deep subsidence of the land surface are significant concerns. These processes can lead to non-linear ecosystem changes and organic matter cycling dynamics, causing ecosystems to shift from sinks to sources of organic matter. Observations indicate that thermokarst thaw processes, triggered by natural disturbances like wildfires, erosion, or excess precipitation, can lead to rapid permafrost degradation, much faster than the gradual thaw predicted by models based solely on rising air temperatures. These events are associated with ground subsidence, alterations in surface hydrology, and changes in vegetation and organic matter cycling. The impact of thermokarst processes on carbon dynamics varies by region but can significantly alter carbon storage and greenhouse gas emissions. While some models estimate that plant growth may offset permafrost carbon release, thermokarst-induced thaw succession models suggest that a substantial amount of carbon may be emitted (Nitzbon et al., 2020; Turetsky et al., 2020), with only limited compensation by plant uptake.

Overall, the vulnerability of permafrost carbon to climate warming and degradation is a complex and dynamic issue (Grosse et al., 2011). It is affected by various factors (Fig. 1), including local hydrology, ground-ice content, but also human land use changes, and the extent of thermokarst processes. These complexities underscore the challenges in accurately predicting the fate of permafrost carbon in a rapidly changing climate.

Organic matter quantity in permafrost

Organic matter inventory

The current inventory of what is termed 'permafrost carbon' pertains to soil organic carbon within the vast northern circumpolar permafrost region (Schuur et al., 2013), which covers an area of approximately 17.8 million km^2, plus inventories in areas of mountain permafrost (Strauss et al., 2021a). Recently, an additional pool has been quantified in permafrost deposits under the shallow Arctic Ocean shelves that were terrestrial landscapes during the Ice Ages (Miesner et al., 2023). This shift in focus to deeper and subsea reservoirs has led to a significant reassessment of the scale of this carbon reservoir, identifying the permafrost region as the largest terrestrial C and N pool on Earth. Strikingly, this inventory has tripled in size previous estimates from 1460 to 1600 gigatons of carbon (Gt C) on land to 4360 Gt for the total permafrost region, including subsea permafrost carbon of 2822 Gt (Table 1). This important revelation has reshaped our understanding of the extent of carbon storage within permafrost-dominated landscapes.

Splitting the organic matter pool into its components

Soils in the terrestrial permafrost region are estimated to store 1000 $\pm$ 200 Gt of organic carbon and 60 $\pm$ 20 Gt of N in the upper 3 m (Table 1 and Fig. 3) (Hugelius et al., 2014; Mishra et al., 2021; Palmtag et al., 2022). Of this total carbon storage, about 330 $\pm$ 80 Gt C is stored in peatlands (Hugelius et al., 2014; Hugelius et al., 2020), and the rest in mineral soil, often enriched in carbon by repeated deposition or frost-heave processes (Tarnocai et al., 2009). When combined with the 2800 Gt C of organic soil carbon found within the same depth range in all other biomes (including permafrost peat) as well as other pools in deep permafrost (500 Gt) and tropical peatlands (50 Gt; Jackson et al., 2017), the terrestrial permafrost region emerges as a significant carbon reservoir, harboring $\sim$30% of the global carbon pool on land in only $\sim$15% of the total global land area (Fig. 4). This revelation

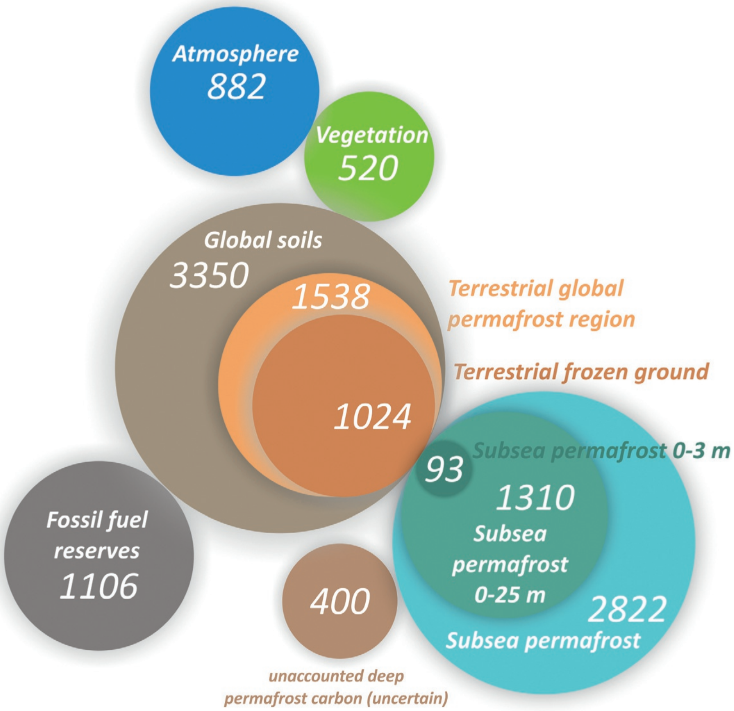

Fig. 3 Terrestrial carbon stocks and atmospheric carbon in relation to the carbon stored in the permafrost region. The size of the circles is proportional to the size of the carbon stock. The C stocks are given in Gt. The global soil estimate (3350 Gt) is based on soils to 3 m depth (2800 Gt) as well as other pools in deep permafrost (500 Gt) and tropical peatlands (50 Gt; Jackson et al., 2017). Based on data from different International Panel on Climate Change (IPCC) reports (e.g., IPCC (2019), Miesner et al., (2023), and Hugelius et al. (2014, 2020). Adapted and updated from Strauss J, Schirrmeister L, Grosse G, Fortier D, Hugelius G, Knoblauch C, Romanovsky V, Schädel C, et al. (2017) Deep Yedoma permafrost: A synthesis of depositional characteristics and carbon vulnerability. *Earth-Science Reviews* 172: 75–86. https://doi.org/10.1016/j.earscirev.2017.07.007.

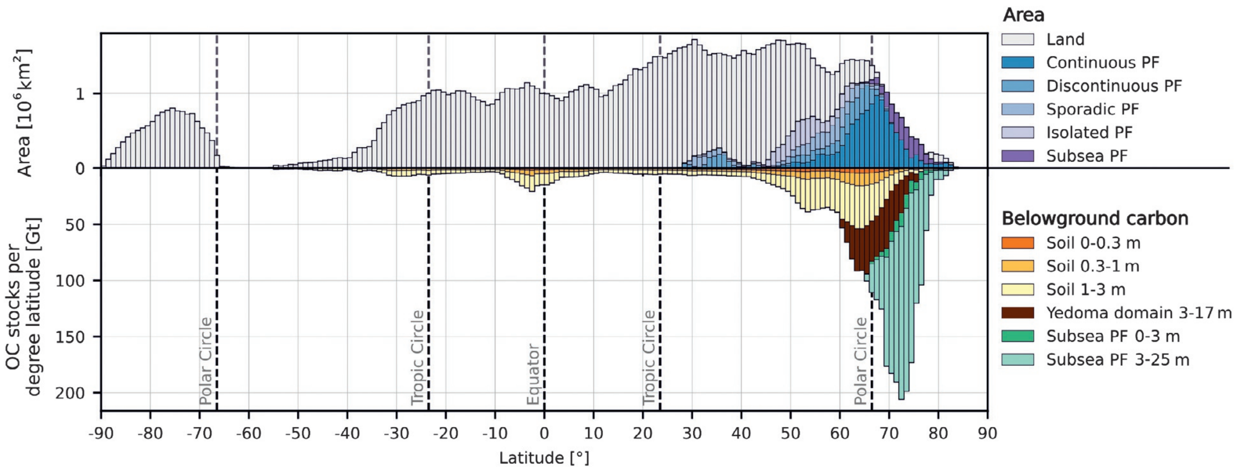

Fig. 4 Latitudinal distribution of belowground organic carbon (OC) in relation to land mass and permafrost coverage. Created with updated data sources (Poggio et al., 2021), different depth classes and including the yedoma regions deep carbon pool (Strauss et al., 2017; Strauss et al., 2021b), as well as the subsea carbon pool (Miesner et al., 2023). The grey and bluish bars on the upper part of the diagram show the area of the land mass per latitude as well as the occurrence of the different types of permafrost (PF) regions. Permafrost from the Southern Hemisphere is not shown in the upper panel.

underscores the remarkable carbon density within this relatively small fraction of the Earth's total soil area. This near-surface carbon pool estimate seems to be reasonable, as the newest estimates have not shifted it significantly (Mishra et al., 2021; Palmtag et al., 2022).

The 30% of total global soil carbon proportion, however, is likely to be a minimum value because substantial permafrost extends deeper than 3 m (e.g., yedoma), and subsea permafrost stores 2822 (1518–4982) Gt C (double the amount stored in lowland permafrost, Miesner et al., 2023), which is not included in the soil area percentage calculation. Notably, yedoma deposits in Siberia and Alaska alone contain 327–466 Gt C (Strauss et al., 2017). Furthermore, Arctic river deltas hold an additional 96 ± 55 Gt C (Hugelius et al., 2014). These reservoirs, though part of the circumpolar inventory, add to the complexity of permafrost carbon dynamics. Moreover, alpine permafrost, distinct from the circum-Arctic and boreal regions, holds a substantial carbon pool, estimated at 83 Gt C (Table 1). This estimate is derived from a combination of global mountain permafrost carbon estimates and updated measurements of carbon stocks in the top 3 m of the Tibetan Plateau. Nearly half of this Tibetan carbon is proposed to be within permafrost. Additionally, there may exist an additional reservoir of deep permafrost carbon, ranging from 350 to 465 Gt C, outside the already accounted Yedoma and delta regions. This calculation considers a depth range of 3–10 m, with a carbon content of 11–14 kg m^{-3} (Schuur et al., 2015) (Fig. 3).

It is essential to recognize that within the permafrost region some of the carbon is frozen and some is unfrozen, and that the extent of these states is uneven and fragmented. As a result, only ~1000 Gt C, as derived from various sources, are stored frozen in permafrost, while an additional 600 Gt C reside in permafrost-free soils or sediments (e.g., the active layer) within the same region. Below the sea, it may be even more complicated: while the deposits comprise permafrost because of its strict temperature definition, some of the deposits (and therefore a fraction of the carbon) are unfrozen because of the sediment's salt content. This nuanced wording underscores the intricate nature of permafrost carbon storage and its potential implications for future climate dynamics.

In addition to carbon, nitrogen (N) stocks in permafrost soils have been estimated to range from 22 to 106 Gt N, with the best estimate standing at 55 (±15) Gt in the first 3 m of soil (Palmtag et al., 2022). Including the deep N estimate of the yedoma domain, this N estimate is 85–97 Gt N (Strauss et al., 2022). A potential release of even a small fraction of this nitrogen as N_2O could amplify the climate feedback associated with permafrost thaw, leading to increased greenhouse gas release (Voigt et al., 2020; Hugelius et al., 2023; Strauss et al., 2024).

Intricate dynamics with degrading permafrost: What is the permafrost carbon pathway for future degradation?

The rising temperatures associated with climate change pose a significant risk to permafrost stability. Permafrost is susceptible to two primary vulnerability factors: physical vulnerability, which refers to exposure to thawing due to degradation processes, and microbiological vulnerability, which pertains to the quality of the organic matter present in the soil. When the conditions lead to high vulnerabilities in both (physical and microbiological), they can result in the release of ancient and deeply stored carbon, significantly disturbing the delicate balance of permafrost carbon dynamics. The ongoing challenge centers on comprehending how shifting environmental conditions might affect the array of mechanisms responsible for stabilizing permafrost (Section "Organic matter stabilization: Preserving organic matter for millennia"). Since we cannot directly measure future developments, we rely on models for estimation. Therefore, predictions regarding future carbon emissions from permafrost are derived from simulations that account for the volumes of organic carbon exposed as the seasonally unfrozen layer gradually deepens during the growing season (e.g., Dobricic and Pozzoli (2019) and related references). Additionally, it is crucial to consider several other processes, including thermokarst processes, to enhance the accuracy of future permafrost carbon emission estimates:

1. Winter season carbon emissions from permafrost: can carbon uptake during the growing season offset winter emissions (as noted by Natali et al., 2019)?
2. Loss of soil organic carbon through lateral hydrologic export implies that carbon emissions do not solely result from gradual soil thawing but can also occur through waterborne pathways that transport organic matter across the landscape (Vonk et al., 2019). This may intensify with increased hydrological connectivity in thawing permafrost environments.
3. Thermokarst: ~20% of the permafrost region is susceptible to deep thawing of ice-rich permafrost, leading to soil collapse and the exposure of deep organic carbon. This not only amplifies carbon emissions but also increases CH_4 emissions due to the formation of lakes and wetlands during the collapse (Turetsky et al., 2020).
4. The rapidly eroding coastlines of the Arctic Ocean and inland result in the collapse of permafrost and the release of frozen organic carbon into the ocean, creating an additional pathway for carbon emissions (Mann et al., 2022; Sanders et al., 2022; Tanski et al., 2017).
5. Abiotic interactions between mineral surfaces and organic carbon (Opfergelt (2020); Liu et al. (2022), have the potential to stabilize organic matter after it thaws, affecting how soil organic carbon stocks respond to global warming.

It is important to note that existing models capable of simulating permafrost carbon emissions do not currently account for these five processes. With this in mind, we discuss briefly the intricate dynamics associated with degrading permafrost. As soils thaw or warm due to climate changes, heightened microbial activity in the soil leads to the release of greenhouse gases, including CO_2, CH_4, and N_2O, into the atmosphere. These emissions contribute to further warming through the permafrost–climate feedback (e.g., Schuur et al. (2022) and references therein).

The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Canadell et al., 2021) estimated that the permafrost greenhouse gas feedback from CO_2 per degree of global warming at the end of the 21st century ranges from 3.1 to 41 Gt C $°C^{-1}$. Moreover, there is an additional permafrost feedback from CH_4 ranging from 0.7 to 7.3 Gt C CO_2-equivalents (CO_2-e) $°C^{-1}$. This does not fully account for thermokarst processes, which release substantial additional CO_2 and CH_4. This particularly occurs in water-logged post-thaw environments (Turetsky et al., 2020). Thermokarst thaw events, including the formation of thaw lakes, collapse of permafrost peatlands, and thaw-slump formation, can rapidly affect permafrost at depths of several meters. This leads to swift melting of ground ice, land subsidence, and a complete restructuring of the landscape. In addition to uncertainties in how climate warming drives increased respiration, there is large uncertainty regarding mediating effects from increased vegetation productivity (and CO_2 uptake) caused by longer growing seasons, increased CO_2 concentrations, and additional nutrient release from thawing permafrost (McGuire et al., 2018; Liu et al., 2022). The absolute size of the permafrost carbon pool relative to the global vegetation carbon pool (Fig. 3) suggests that a short-term vegetation carbon sink may offer only a limited capacity to offset permafrost carbon losses. While model uncertainties remain large, many studies based on observational greenhouse gas flux time series show enhanced net greenhouse gas emissions from warming and thawing permafrost soils (Natali et al., 2015; Voigt et al., 2019; Kuhn et al., 2021; Marushchak et al., 2021; Rodenhizer et al., 2022).

Predicting a potential transition from permafrost being a net greenhouse gas sink to a source remains a complex challenge also when using Earth system models (ESMs). A recent study employing the Coupled Model Intercomparison Project Phase 6 (CMIP6) ensemble of ESMs foresees a continued capacity for northern regions to absorb CO_2 from 2015 to 2100 across a wide range of human emissions scenarios (Qiu et al., 2023). However, it is crucial to note that most CMIP6 models lack explicit representations of even permafrost or the greenhouse gas feedbacks resulting from thaw, making them likely unable to accurately forecast shifts in the permafrost greenhouse gas balance in response to future warming. A prior comparison of process-based models that incorporate gradual permafrost thaw revealed that, under moderate emission scenarios (Representative Concentration Pathway 4.5; RCP4.5), the northern permafrost region is expected to continue acting as a net carbon sink. However, under higher emissions scenarios, especially over the long term, it is likely to transition into a carbon source (McGuire et al. (2018). It is important to acknowledge that these findings exhibited significant variation among different models, primarily due to their limited representation of processes influencing vegetation productivity, soil respiration, and permafrost dynamics.

With these limitations in mind, we focus now on scenarios depicting future carbon emissions in the Arctic within a warming global context and their potential ramifications for Earth's climate. Drawing from published projections (Schuur et al., 2022 and references therein), scenarios encompass a broad spectrum of possibilities concerning the effects of Arctic carbon emissions on climate warming. Thus, we span low, medium, and high ranges for both CO_2 and CH_4 emissions.

CH_4 emissions span 0.9–11.9% of the total carbon emissions across these scenarios, with an average of 4.2% and a median of 3.3% (Schuur et al., 2022). To comprehensively assess the combined impact of CO_2 and CH_4 emissions on climate, we employ a conversion method to express CH_4 mass in terms of carbon dioxide equivalent (CO_2-e). This analysis reveals that CH_4 emissions contribute 11–69% to a warming effect across the scenarios, with an average of 37%. Interestingly, the relative influence of CO_2 versus CH_4 emissions varies, underscoring that the role of CO_2-induced climate forcing should not be underestimated, despite methanes's higher global warming potential. In fact, CO_2 remains the dominant contributor to climate forcing in six out of the nine scenarios (Fig. 5). In total numbers in these scenarios, the cumulative greenhouse gas emissions (in CO_2-e), encapsulating both the influence of CO_2 and the greater warming potential of CH_4, span a range of 55–232 Gt C CO_2-e (Fig. 5).

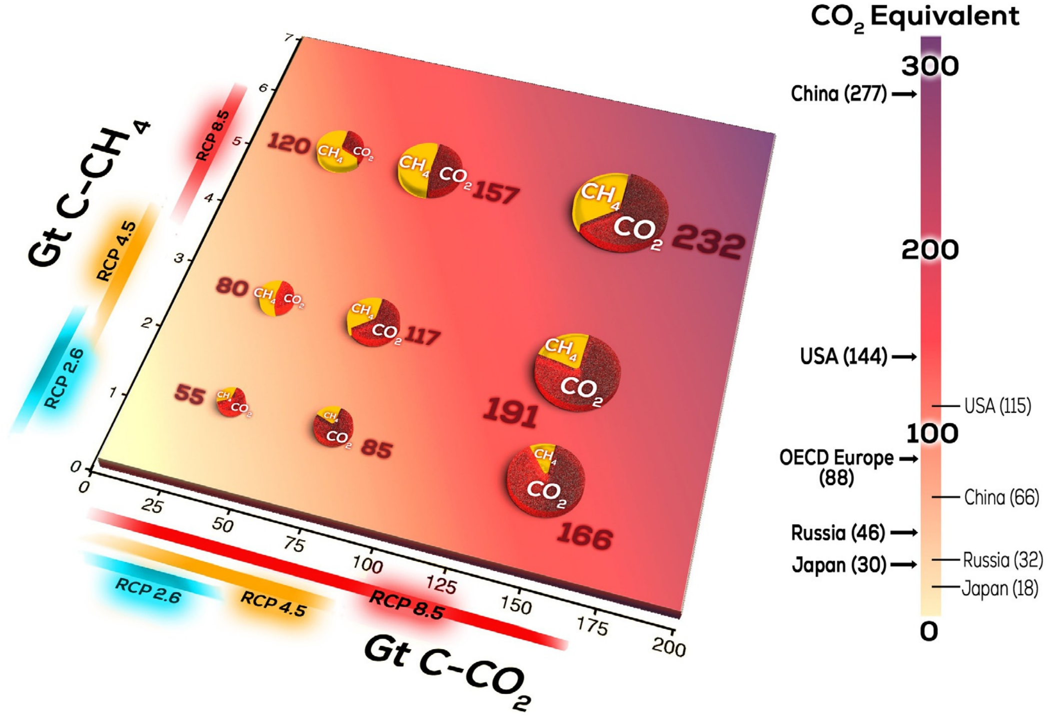

Fig. 5 Visualization of nine scenarios illustrating the cumulative projected emissions of greenhouse gases over the period 2000–2099. These scenarios are based on three levels of net CO_2 emissions (low, medium, high) and three levels of net CH_4 emissions (low, medium, high) into the atmosphere. The x- and y-axes represent the cumulative mass of carbon (in gigatons) contained in either CO_2 or CH_4, in addition to the preindustrial background carbon exchange. The color scale represents the total greenhouse gas equivalents, measured in gigatons of carbon as carbon dioxide equivalent (Gt C CO_2-e) units, taking into account the weighting of CH_4 relative to CO_2. We also provide comparisons with extrapolated (to the year 2099) 2019 country-level carbon emissions (in Gt C CO_2-e) on the left side and historical (1850–2021) country-level fossil fuel carbon emissions (in Gt C CO_2-e) extrapolated to 2099 on the right side for several representative nations. The size of each pie chart corresponds to the total CO_2-e for each specific scenario, and the cumulative Gt C of CO_2-e labeled under each pie chart shows the relative contributions of CO_2 and CH_4 to the total CO_2-e. It is important to note that these nine scenarios, for which emissions were quantified, do not cover the upper limits of the CO_2 and CH_4 emissions axes. There remains a possibility of upper-end scenarios, either higher or lower, that fall outside the range depicted in these nine scenarios after a decade of projections. Modified from Schuur EAG, Abbott BW, Commane R, Ernakovich J, Euskirchen E, Hugelius G, Grosse G, Jones M, et al. (2022) Permafrost and climate change: Carbon cycle feedbacks from the warming Arctic. *Annual Review of Environment and Resources* 47: 343–371. https://doi.org/10.1146/annurev-environ-012220-011847, drawn by Victor Leshyk.

Furthermore, the evaluation shown in Fig. 5 includes the potential comparison of Arctic carbon emissions with emissions at the level of entire countries, a crucial aspect in discussions concerning climate change mitigation strategies. In certain scenarios, the cumulative emissions from the Arctic are on par with or even surpass the emissions of entire nations over the course of a century, underscoring the unique challenges posed by the 'country of permafrost (Schuur et al., 2022). As an example, the lowest scenario entails cumulative emissions greater than Russia's 2019 emissions over 100 years, or equivalent to the emissions of two Japans over the same period. This particular scenario, and aligned global temperature targets, highlights the necessity of factoring in Arctic carbon emissions when formulating climate strategies. Moreover, other greenhouse gases like N_2O, or gas hydrates below the permafrost, are not included in the model calculations visualized in Fig. 5. Likewise, subsea permafrost in general is not included as it is still very unclear how much gas could be released if in the first place, and how much of it ends up in the atmosphere after passing through the overlying water column (Miesner et al., 2023).

This release of permafrost carbon acts as an accelerator of climate change. But it does not overshadow emissions from fossil fuels, as current anthropogenic CO_2 emissions are at least 10 times higher than emissions from thawing permafrost. On the other hand, the reduction of global warming to well below 2 °C above pre-industrial levels envisaged by the Paris Agreement of 2015 will require diminishing anthropogenic emissions in the first half of the 21st century. In this case, future CO_2 emissions from permafrost may become comparable to anthropogenic emissions, and Paris Agreement targets to reduce global warming may be exceeded sooner than expected. The quota of CO_2 that humankind can emit to keep below the agreed level of global warming will likely diminish, and additional efforts for achieving Paris Agreement goals will be required (Dobricic and Pozzoli, 2019).

Mitigation effects on permafrost greenhouse gas release

The IPCC Special Report on Oceans and Cryosphere in a Changing Climate (IPCC, 2019) has emphasized the alarming consequences of an Arctic region undergoing warming. Unless substantial efforts are made to mitigate climate change, the Arctic is on track to release between 5 and 15% of the terrestrial permafrost carbon, totaling tens to hundreds of billions of tons of CO_2 and

CH_4 into the atmosphere by 2100. If the Arctic becomes a net carbon source of approximately 1 Gt C annually by 2100, primarily due to gradual permafrost thawing, the simultaneous release of both CO_2 and CH_4 could result in an annual equivalent of around 2 Gt C CO_2-e. Over centennial timescales, this estimate could climb to nearly 3 Gt C CO_2-e if these models accurately depict accelerated permafrost thaw rates (Schuur et al., 2022). Conversely, the possibility of increased vegetation and biomass in high latitudes, often referred to as 'greening', could partially offset CO_2 emissions, aligning with ESMs that simulate permafrost thaw from the top down.

Irrespective of the balance between organic carbon release and uptake in the Arctic ecosystem, one undeniable fact remains: reducing the main greenhouse gas emissions (the human-induced carbon emissions) through climate mitigation measures will slow the rate of change in the Arctic, decelerate permafrost thawing, and limit disruptions to the carbon cycle, potentially reducing Arctic carbon emissions. For instance, projections indicate that the spatial extent of near-surface permafrost could decrease by $\sim$69 $\pm$ 20% in the absence of climate policies, as under RCP8.5. In contrast, with climate policies aimed at constraining global warming to below 2 °C (as in RCP2.6), this reduction would be lessened to 24 $\pm$ 16%. This signifies that permafrost loss will persist even with mitigation efforts, but without such measures, the loss would be 145% greater. Recent findings from CMIP6 models corroborate this trend, projecting a linear decline in near-surface permafrost volume per degree of mean global warming. In addition, an overshooting pathway, which is a situation in which humans 'buy time' and the concentration of greenhouse gases in the Earth's atmosphere temporarily exceeds a desired threshold (e.g., maximum of 1.5 °C warming), before eventually returning to or stabilizing at that target level is complicated with permafrost organic matter. Overshoot warming will likely trigger continued permafrost thaw that drives additional warming for centuries even after the climate stabilizes, and likely brings the need to compensate for much more carbon (e.g., overshoot carbon plus additional C emissions from thawing permafrost resulting from the overshoot-caused warming) by negative emission.

Conclusion

The Arctic's terrestrial organic matter storage is undergoing significant transformations due to several key factors. The Arctic is experiencing rapid temperature increases, far surpassing global averages, and record-high permafrost temperatures, signaling its warming trend. Within the northern circumpolar permafrost region, there exists an immense reservoir of organic matter, estimated at approximately 1460–1600 Gt C on land. This amount is almost double the carbon present in Earth's atmosphere and significantly surpasses the carbon stored in plant biomass, woody debris, and litter combined across boreal and tundra biomes. Additionally, there is a reservoir of about $\sim$2800 Gt C in seafloor permafrost sediments, along with 36 Gt C in permafrost outside the Arctic, such as in northern China and the Tibetan Plateau. The concept of thermokarst-caused thaw in thick ice-rich permafrost leads to permafrost degradation at a much faster rate than gradual warming alone. Approximately 20% of the Arctic's landscape, characterized by substantial ground-ice content, is susceptible to these deep thaw processes that may affect frozen ground that sequestered at least half of the permafrost carbon pool. This process not only degrades permafrost but also alters ecosystem types and affects the release of CO_2, CH_4, and likely N_2O emissions.

Projections for cumulative additional net greenhouse gas emissions by 2100 encompass nine scenarios, characterized by combinations of low, medium, and high CO_2 and CH_4 emissions. These scenarios combine the effects of CO_2 and CH_4 and range from 55 to 232 Gt C of carbon dioxide equivalent (GtC CO_2-e). For context, the 2019 emissions over a century for key nations were 46 Gt C—CO_2 for Russia, 88 Gt C CO_2-e for OECD Europe, 144 Gt C CO_2-e for the United States, and 277 Gt C CO_2-e for China. While the concerns of an abrupt 'permafrost greenhouse gas bomb' releasing massive greenhouse gas emissions in a short period are not confirmed, there is evidence that permafrost destabilization increases the likelihood of the Arctic transitioning from a carbon sink to a continuous carbon source. Permafrost remains a critical component of the climate system, underscoring the need to incorporate deep permafrost carbon reserves and rapid thaw processes into the next generation of ESMs.

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