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Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic

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Abstract

Rapid Arctic environmental change affects the entire Earth system as thawing permafrost ecosystems release greenhouse gases to the atmosphere. Understanding how much permafrost carbon will be released, over what time frame, and what the relative emissions of carbon dioxide and methane will be is key for understanding the impact on global climate. In addition, the response of vegetation in a warming climate has the potential to offset at least some of the accelerating feedback to the climate from permafrost carbon. Temperature, organic carbon, and ground ice are key regulators for determining the impact of permafrost ecosystems on the global carbon cycle. Together, these encompass services of permafrost relevant to global society as well as to the people living in the region and help to determine the landscape-level response of this region to a changing climate.

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INTRODUCTION

Unprecedented environmental change occurring in the Arctic, in the broad sense of the Circumpolar North (1), has important consequences for society. Declining sea ice, shrinking ice sheets and glaciers, and degrading permafrost (perennially frozen ground) directly affect the function of local ecosystems and the well-being of people. At the same time, the impact of a changing Arctic extends far beyond the region, altering the lives of people everywhere on Earth. Declining sea ice

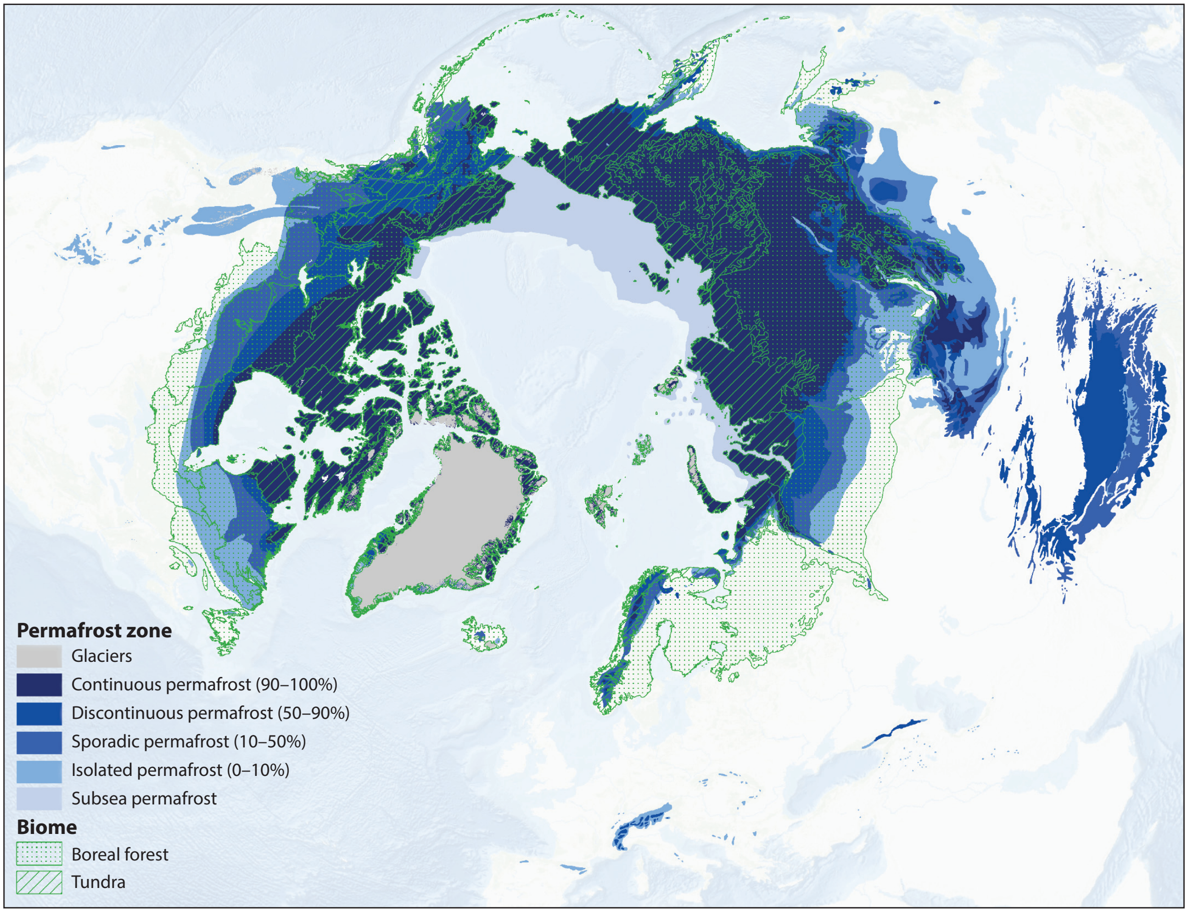

Figure 1

Permafrost region with zones shown in blue shades, with percent of ground underlain by permafrost in parentheses. Generalized biome area for tundra and boreal regions shows intersection with permafrost ground across some, but not all, of the region. Data derived from References 143 and 144.

reduces reflection of sunlight and directly warms the Earth, shrinking ice sheets and glaciers contribute to sea level rise (2), and degrading permafrost releases additional greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) into the atmosphere (3). Permafrost is the thermal state of subsurface ground. This means that, unlike sea ice, glaciers, and ice sheets, permafrost defies direct observation through satellite remote sensing at local to global scales. Instead, detecting permafrost change requires subsurface measurements and/or indirect remote sensing assessments and, as such, our understanding of change remains patchwork even in the face of record-setting warming observed in the permafrost borehole monitoring network (4). Here, we focus on degrading permafrost (**Figure 1**), summarizing the latest knowledge of the impact on the global carbon cycle and the feedback to climate change. Over the past several decades, the study of permafrost has grown beyond its geophysical roots to more fully realize the interplay between geophysical, hydrobiogeochemical, and ecological processes that define ecosystem function and the dynamics of the carbon cycle (5, 6). This review serves as a roadmap for this growth in permafrost

Arctic: the terrestrial northern circumpolar region that comprises the continuous and discontinuous permafrost zones, the tundra biome, and the parts of the boreal biome characterized by cryosphere elements, such as permafrost and persistent winter snow cover

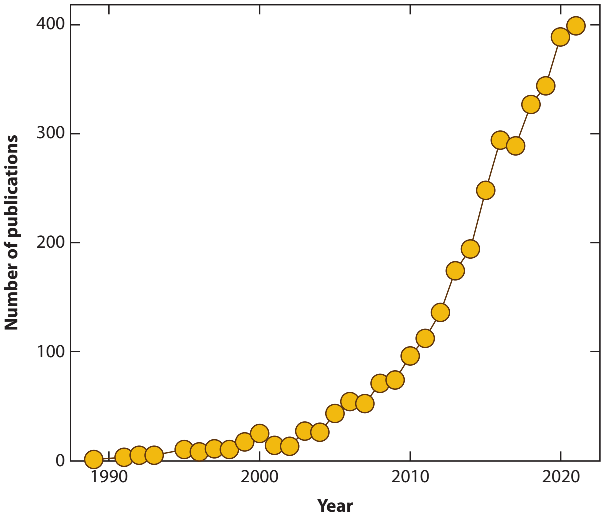

Figure 2

Permafrost carbon literature by year of publication. Data collected from ISI Web of Science with "permafrost" and "carbon" as search terms within the title, abstract, author key words, and KeyWords Plus. Publications from 2000 to 2021 represent 96% of all publications; from 2005 to 2021, 91%; and from 2010 to 2021, 80%.

science (6) and a path through the key science literature of permafrost carbon and climate change (**Figure 2**).

Permafrost is not permanent anymore. It was originally narrowly defined as ground with a temperature at or below 0°C for at least two consecutive years (7), essentially marking the long-term phase change from liquid water to ice. Its distribution depends on regional and global climate conditions (8, 9), the dynamics of ecosystems through ecological succession (10, 11), and the impacts of people on permafrost ecosystems (12, 13). Record high temperatures at ~10–20-m depth in the permafrost (near or below the depths affected by intra-annual fluctuation in temperature) have been documented at many long-term monitoring sites in the Northern Hemisphere circumpolar permafrost region (4), marking temperature increases occurring throughout the entire soil/ground profile. During the decade between 2007 and 2016, the rate of increase in permafrost temperatures was 0.39 ± 0.15°C for colder continuous zone permafrost monitoring sites and 0.20 ± 0.10°C for warmer discontinuous zone permafrost (4). Relatively smaller increases in permafrost temperature in warmer sites indicate that permafrost is thawing, with heat instead being absorbed by the ice-to-water phase change. However, the importance of permafrost goes beyond temperature. Ecological and geomorphological processes are highly sensitive to the phase change between ice and water. This transition point makes the structure and function of permafrost ecosystems unique and simultaneously vulnerable to major change in a warming climate. Here, we take a wider view to include the composition of permafrost ground (**Figure 3**). In particular, the ice content and the soil organic carbon in frozen ground are key regulators of the impact of permafrost thaw on the global carbon cycle in a changing climate (14). Together, temperature, organic carbon, and ice encompass services of permafrost relevant to global society as well as to the people living in the region (5).

This article connects new scientific literature and extends beyond past reviews, presenting the latest knowledge about the size of the organic carbon pool stored in permafrost and the potential

Permafrost: ground (rock or soil, including ice and organic material) that remains at or below 0°C for at least two consecutive years

Frozen ground: soil or rock in which part or all of the pore water consists of ice

Permafrost degradation: decrease in the thickness and/or areal extent of permafrost

Permafrost carbon: organic soil carbon within the permafrost region including non-permafrost soil orders and the surface active layer frozen only in winter

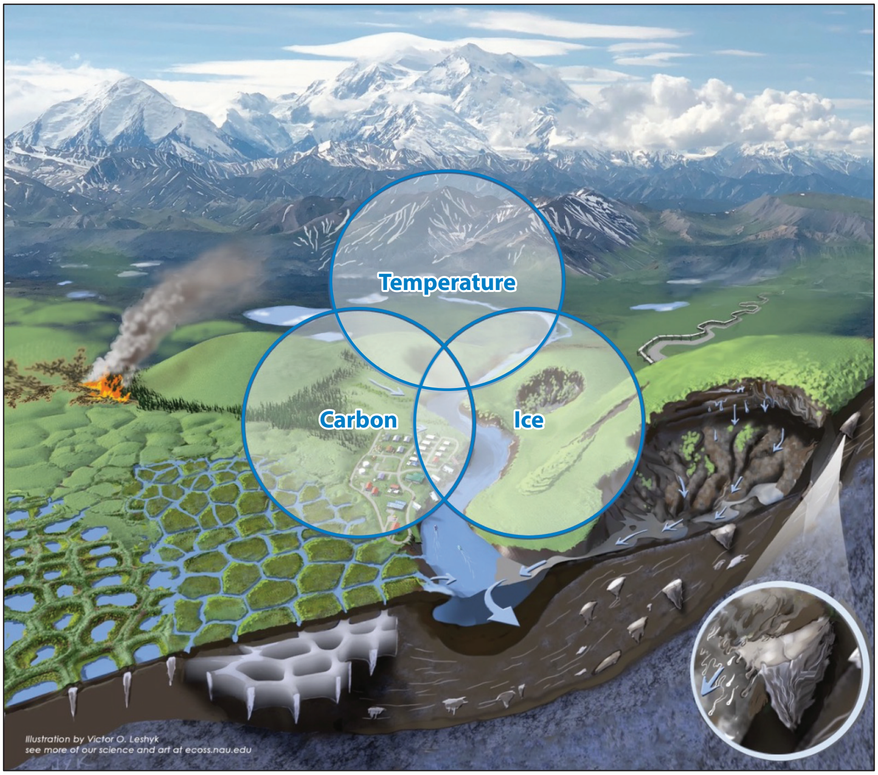

Figure 3

Permafrost landscape with three components of frozen ground (temperature, ice, and carbon) that comprise key ecosystem services to people. Temperature and time comprise the classical definition of permafrost. The amount of moisture/ice determines the structural integrity of frozen ground in the face of permafrost thaw. The amount of organic carbon determines the impact on atmospheric composition and climate as the greenhouse gases CO_2 and CH_4 are released from thawing permafrost. Illustration by Victor O. Leshyk.

for permafrost thaw—with its associated landscape changes in ecology and hydrology—to influence the climate system. Synthesizing across a range of methodologies and estimates, this article culminates by presenting a suite of Arctic carbon emission scenarios with associated narratives that describe potential future warmer worlds that we may inhabit. The future warmer world is likely to contribute significant Arctic carbon emissions, much like a "country of permafrost" that we should be considering as we design human emission targets to stabilize global warming. In sum, this synthesis presents future permafrost carbon emissions in a unique way that aligns with the full breadth of knowledge in this rapidly expanding scientific field.

PERMAFROST CARBON POOL

Northern soils were known for decades to have relatively large amounts of organic carbon—the remains of plants, animals, and microbes that lived and died over hundreds to thousands of years—in particular stored in waterlogged peatlands (15). But only more recently has attention focused on organic carbon stored deep in permafrost mineral soils (16), including below the 1-m depth that is the traditional zone of soil accounting (17). The current estimated inventory of so-called permafrost carbon (18)—organic soil carbon within the northern circumpolar permafrost region

Permafrost thaw: progressive loss of ground ice in permafrost; during thaw, temperature fluctuations are subdued as energy converts ice to water

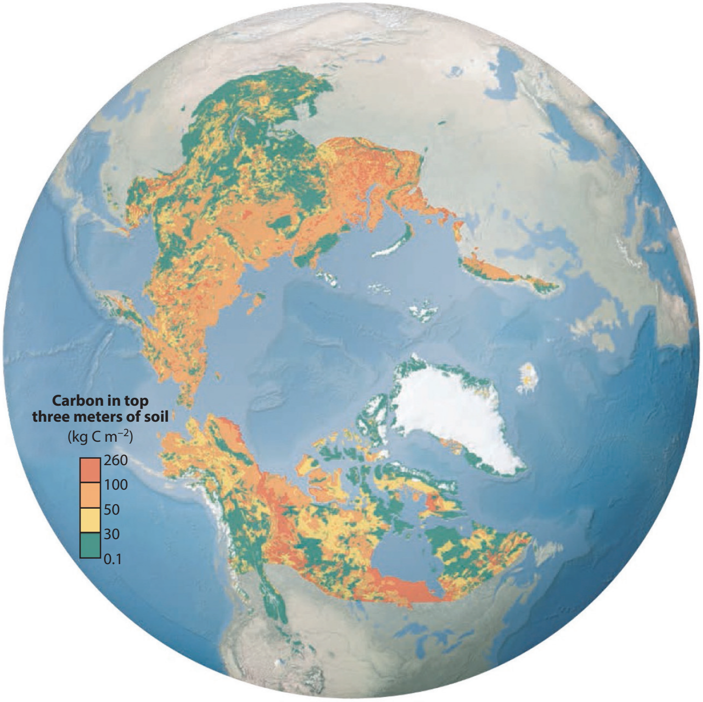

Figure 4

Organic carbon content of near-surface (0–3-m soil depth) northern circumpolar permafrost region soils. Carbon density is reported in kg C m^{-2} to 3-m depth. The total near-surface soil carbon for the northern circumpolar region is 1,035 ± 150 Pg C. Data are from References 19 and 20.

(17.8 × 10^6 km^2 area)—tripled to 1,460–1,600 petagrams of carbon (Pg C; 1 billion metric tons carbon) (1) (**Figure 4**). Near-surface permafrost soils (0 to 3 m in depth from the surface) contain 1,035 ± 150 Pg C (19, 20). When added to the 2,050 Pg C of organic soil C (from 0- to 3-m depth) contained in all other biomes, the permafrost region represents 33% of the global pool stored in only 15% of the total global soil area (3). This near-surface carbon pool estimate seems to be converging as the newest estimates have not shifted this total significantly (21, 22). However, the 33% of total global soil carbon proportion is likely to be a minimum since substantial permafrost carbon exists below 3-m depth and probably in higher quantities than organic carbon in deep (>3-m) soils of other biomes. In particular, the Yedoma deposits of Siberia and Alaska contain 327–466 Pg C (23), and Arctic river deltas contain 96 ± 55 Pg C (19), both of which are counted in the total inventory above. Permafrost carbon not counted in the total circumpolar inventory estimate includes 36 Pg C in the Qinghai-Tibet Plateau and northern China, the deep deposits outside the Yedoma region roughly estimated at 350 to 465 Pg C (3, 24), and an expert assessment of ~560 Pg C in the subsea permafrost region that was formerly a terrestrial permafrost environment when sea level was lower during the Last Glacial Maximum (25). Together, these soil pools contain an order of magnitude more organic carbon than contained in plant biomass (55 Pg C), plus woody debris and plant litter (45 Pg C) in the same region (24), suggesting that carbon release from soils to the atmosphere could outweigh the potential for carbon gain by plants.

Near-surface permafrost: permafrost within ~3–4 m of the ground surface, which is especially relevant for people and ecosystems

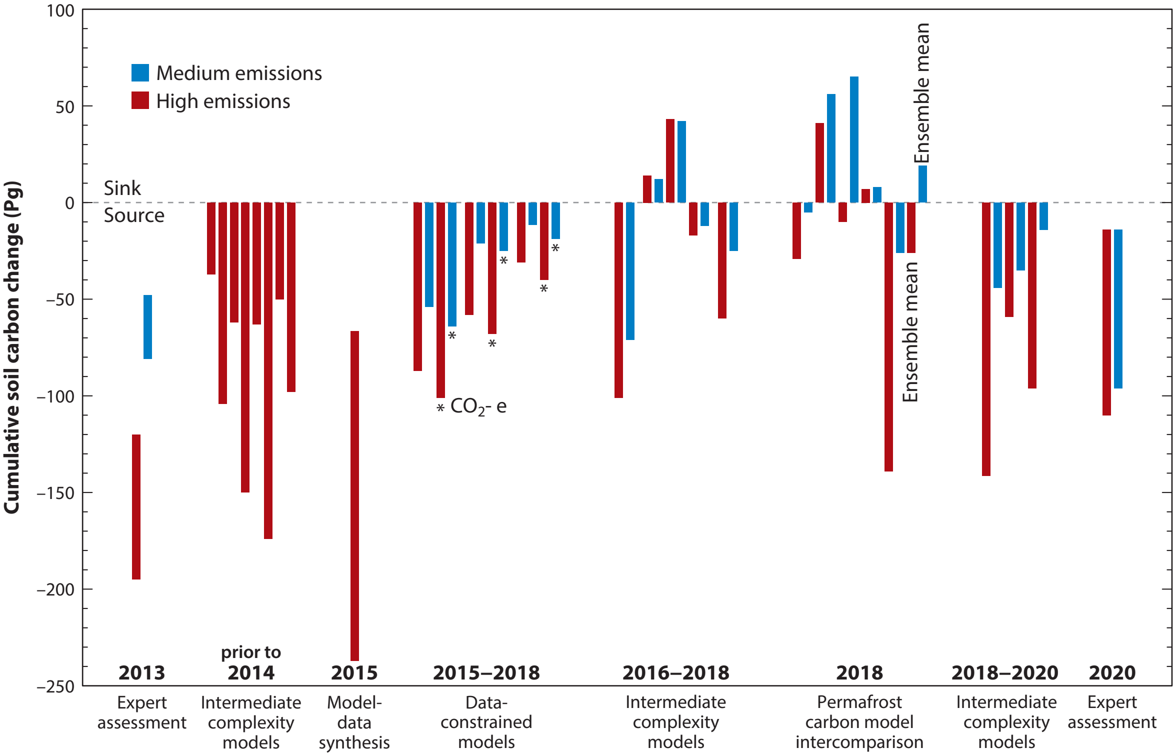

Figure 5

Estimates of cumulative net soil carbon pool change for the northern circumpolar permafrost region by 2100 following medium and high emission scenarios (e.g., RCP4.5 and RCP8.5 or equivalent). Cumulative carbon amounts are shown in petagrams C (1 Pg C = 1 billion metric tons or 1×10^{15} g C), with source (negative values) indicating net carbon movement from soil to the atmosphere and sink (positive values) indicating the reverse. Some data-constrained models differentiated CO_2 and CH_4. Bars show total carbon by weight; paired bars with asterisks indicate CO_2-equivalent (CO_2-e), which takes into account the global warming potential of CH_4. Ensemble mean bars refer to the model average for the Permafrost Carbon Model Intercomparison Project (five models). Bars that do not start at zero are in part informed by expert assessments and are shown as 95% confidence interval ranges; all other bars represent model mean estimates. Data are from References 18 and 33 (eight models); see also References 3, 25–27, 30, 48, 52, 145–149. The final expert assessment (25) represents subsea permafrost emissions and represents a different geographic area of permafrost, in contrast to all other estimates that represent overlapping geographic areas.

FEEDBACK TO CLIMATE

Overview

Soil carbon in the permafrost region is a significant, climate-sensitive component of the global carbon cycle, containing at least twice as much carbon as the atmosphere (3, 14, 19, 20). The impact of this carbon pool on global climate depends on (*a*) how much of this carbon is released to the atmosphere as greenhouse gases; (*b*) what the timescale of the release is; (*c*) what proportion of the release, integrated across the region, is CH_4 versus CO_2; and (*d*) how much of this release is offset by increased plant biomass and new inputs to the soil carbon pool (18) (**Figure 5**). A comprehensive synthesis estimated that CO_2 and CH_4 emissions from thawing permafrost across the Arctic region could release between 5 and 15% of the permafrost carbon pool over decades and centuries under business-as-usual warming scenarios [Representative Concentration Pathway (RCP) 8.5], rather than as a catastrophic pulse release on the scale of a few years (3). This

Representative Concentration Pathways (RCP): scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases, aerosols and chemically active gases, and land-use change

Thermal erosion: combined action of convective heat transfer from flowing water allowing rapid melt of ice and mechanical erosion

proportion is equivalent to a cumulative 67–237 Pg C by 2100. This magnitude of annual release of ∼0.5–2 Pg C per year will act as an important accelerator to climate change on a similar scale to land-use change (deforestation), while at the same time clearly not overshadowing larger global emissions from fossil fuels. Methane emissions from thawing permafrost (included within that total ∼0.5–2 Pg C per year estimate) are projected to cause 40–70% of total permafrost-affected radiative forcing in this century, even though CH_4 emissions are much less than CO_2 by mass (26, 27). Carbon dioxide and CH_4 emissions from permafrost carbon together are expected to accelerate the pace of climate change but do not diminish the importance of human emissions in overall climate change and as the key place for mitigation efforts (28).

Global Model Estimates

The Permafrost Carbon Network Earth System Model intercomparison project (PCN-MIP), completed in the period following the synthesis detailed above, showed a smaller multimodel ensemble mean estimate of 26 Pg C cumulative soil carbon release by 2100 under RCP8.5 (29, 30) (**Figure 5**). This lower modeling estimate was caused by a stronger plant carbon uptake response than obtained by previous Coupled Model Intercomparison Project (CMIP) 5 modeling studies (31). In the PCN-MIP, plant carbon uptake completely offset permafrost carbon release for at least this century as a result of CO_2 fertilization and enhanced growth in a warmer climate. It was not until several centuries later where plant uptake was overwhelmed by soil carbon release; the PCN-MIP also projected the net loss of hundreds of Pg C of permafrost carbon to the atmosphere under RCP8.5, but not reaching those levels until the year 2300. There are significant policy implications for people if plant carbon uptake pushes net Arctic carbon release into the future for several centuries. At the same time, there is increasing understanding that the way global models simulate permafrost as gradual, top-down thaw induced by a warming atmosphere may be overly simplistic such that they underestimate true rates of thaw and impacts on the carbon cycle. Indeed, most of the state-of-the-art Earth System Models (ESMs) used to inform the latest Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) did not contain basic ecosystem structural properties such as carbon in depth-resolved soil layers, which are thought to be essential to simulate emissions as a consequence of top-down thawing of permafrost by a warming climate (29, 32, 33). Nor do many of these models consistently track CH_4 explicitly, which, along with surface hydrology (34), is key for understanding the full impact of Arctic carbon emissions on climate (35).

Abrupt Thaw

A wealth of observations from the permafrost region suggests that nonlinear thresholds (tipping points) at the local scale are likely to play a major role in the dynamics of ecosystem change, making gradual top-down thaw as simulated by ESMs only part of the story. Ground ice is a feature of permafrost, ranging from soil pore ice, centimeter-scale ice lenses and networks, up to massive networks of ice characteristic of fine-grained sediments and soils that restrict water drainage. Excess ice is widespread, ranging for example from 40% of total volume in some sandy soils up to 80–90% of total volume in fine-grained soils (11, 23, 36, 37). With warming and permafrost thaw, loss of excess ground ice causes the land surface to subside and collapse into the volume previously occupied by ice, resulting in disturbance to the overlying ecosystems and human infrastructure (28, 38, 39). Furthermore, the initial ground subsidence caused as permafrost starts to thaw then alters the surface hydrology of permafrost landscapes. Surface water channeling toward subsided areas further degrades permafrost through advective heat transport, or thermal erosion, and ponding water also increases ground heat flux. Thermal erosion includes physical erosion of soil and sediment materials and further exposes deeper permafrost to continued degradation (40). These local hydrologic effects can cause abrupt change in permafrost at point locations much faster than changes in air temperature alone would predict (41, 42). This abrupt thaw process (28) results in microtopographic patterns of subsided ground, where polygonal networks of melting ground ice cause subsequent ecosystem disturbance and form what is called thermokarst terrain (43). Anthropogenic and natural disturbances can accelerate abrupt thaw (10) with profound effects on surface water connectivity and overall drainage conditions (44). Remote sensing across large regions has demonstrated the widespread importance of abrupt thaw across changing permafrost landscapes (45, 46). Melting ground ice that took millennia to form and erosion of soil are essentially permanent on timescales of tens to hundreds of years in a warming Arctic, with irreversible impacts on ecosystem carbon dynamics (14).

Research at the global scale that links these effects across both lowlands and uplands showed that 20% of the northern permafrost region was considered susceptible to past and future abrupt thaw (47). Importantly, this area also stores 50% of the near-surface soil carbon showing the correlation between carbon and ice accumulation that heightens the risk of abrupt thaw to climate change. Since ESMs do not simulate abrupt thaw, dynamics of ecosystem change including carbon cycling have been represented by a different class of regional models that track soil carbon losses as well as carbon gains from plant growth through ecological succession following abrupt thaw. The most comprehensive of these succession models that included the response of abrupt thaw across uplands and lowlands found that an additional 40% more net ecosystem carbon (80 ± 19 Pg C) would be released by 2300 (48) as compared to the ensemble estimate of net ecosystem carbon release from the PCN-MIP (30), which as described previously, only tracked the effect of gradual top-down permafrost thaw as the climate warms. Most of this additional 40% carbon release is attributed to new abrupt thaw features that cover <5% of the permafrost region. Moreover, plant growth in the succession model offset approximately 20% of the permafrost carbon release, a much lower proportion as compared to the estimate from ESMs in the PCN-MIP. Furthermore, the abrupt thaw succession model could track CH_4, in contrast to the PCN-MIP, which did not, and showed that approximately 20% of the net carbon loss from abrupt thaw could be emitted as CH_4, which contributed 50% of the radiative forcing due to its higher global warming potential. These findings are consistent with other abrupt thaw models that considered subsets of the Arctic permafrost landscape such as lake expansion in lowlands (26, 27).

Abrupt thaw: loss of ground ice resulting in subsidence, redistribution of surface water perched on permafrost, and subsequent erosion that exposes deeper permafrost to thaw more rapidly than with changing temperature alone

Thermokarst terrain: characteristic landforms resulting from processes such as collapse, subsidence, and erosion following the melting of ground ice in permafrost

Carbon source: an ecosystem losing net carbon into vegetation and soils, usually over a season, year, or longer

Greening: consistent increases in vegetation productivity characterized by increases in biomass and/or northward expansion of trees and shrubs over decadal timescales

MITIGATION EFFECTS ON PERMAFROST CARBON RELEASE

The IPCC Special Report on Oceans and Cryosphere in a Changing Climate reported in the Summary for Policymakers that the warming Arctic will lead to the cumulative release of tens to hundreds of billions of tons of permafrost carbon as CO_2 and CH_4 to the atmosphere by 2100 with little or no climate mitigation policies (e.g., RCP8.5). If the warming Arctic becomes a net carbon source of ∼1 Pg C per year by 2100 through gradual top-down thawing of permafrost, the release of both CO_2 and CH_4 may make this equivalent to a ∼2 Pg C-CO_2-e per year source if the abrupt thaw succession models correctly estimate CH_4, and up to an almost ∼3 Pg C-CO_2-e per year source over the long term (several centuries) if they correctly project faster permafrost thaw rates. These amounts do not diminish the lead role of human-caused fossil fuel emissions but are highly significant in comparison to other known climate feedbacks, and are still not currently widely represented within ESMs (49), as described above. On the flip side, an increase in plant growth and biomass (greening) of the high latitudes does have the potential to offset at least some of the CO_2 emissions, as projected by the ESMs simulating top-down permafrost thaw.

Whichever way the net ecosystem carbon balance tips regarding carbon release versus uptake, one thing is exceedingly clear: Reducing human carbon emissions through climate mitigation will dampen change in the Arctic, slow permafrost thaw, and reduce changes to the carbon cycle, potentially decreasing Arctic carbon emissions. For example, near-surface permafrost area is projected to decrease by 69 ± 20% by 2100 with no climate policy (RCP8.5), whereas it will decrease by 24 ± 16% with climate policies that aim to limit global warming to under 2°C (RCP2.6) (50). Some permafrost will still be lost even when limiting warming, but there would be 145% more loss without mitigation efforts. The latest ESMs support these findings and project a linear loss of near-surface permafrost volume per degree of mean global warming (51). This continued loss of permafrost even when warming is limited highlights the need to understand carbon emissions under low emission scenarios. Mitigation efforts will not only need to constrain human sources of carbon emissions but will also need to account for uncontrolled sources such as Arctic carbon emissions within allowable carbon budgets (49, 52). These Arctic carbon emissions are likely on the order of a few tens of Pg C of carbon release cumulative by 2100 when global warming is kept under 2°C (RCP2.6) (53–55), but again CH_4 release and abrupt thaw probably increase the net impact on climate proportionately similar to no-climate policy scenarios (e.g., RCP8.5). Given the tipping point aspects of the permafrost carbon system, however, it is simplistic to assume that permafrost emissions scale linearly with the degree of warming. In particular, the abrupt thaw successional models have already pointed to such nonlinear surprises even while acknowledging our limited understanding of them (48). Furthermore, attempts to limit global warming can take many pathways to a future temperature target with implications for how much additional Arctic carbon emission must be accounted for. If an eventual temperature target of 2°C by 2100 is initially overshot by 0.5–1.5°C, this will require accounting for additional tens of Pg C of Arctic carbon emissions. This amount would be on top of those tens of Pg C estimated to be released at 2°C warming due to additional permafrost carbon emissions triggered by the higher overshoot temperature levels (52, 56–59).

WHAT DO ARCTIC CARBON EMISSIONS LOOK LIKE: PAST, PRESENT, AND FUTURE?

This review focuses primarily on scenarios of future Arctic carbon emissions in a warmer world and the potential impact on Earth's climate. This will largely be determined by regional net CO_2 and CH_4 emissions together and, in particular, changes in these emissions relative to the historical past. In this section, future emission scenarios of these greenhouse gases are considered individually and together in the context of a brief overview of past and present emissions.

CARBON DIOXIDE EMISSIONS: OBSERVATIONS

Given the size of the Arctic region, the rugged environmental conditions, and limited accessibility, it has been a challenge to detect carbon cycle change over the region as a whole. There are notable well-studied sites with a history of scientific research that have provided a wealth of mechanistic insight, but the limited number has been a barrier toward understanding and quantifying the aggregate response of the entire region (60–66). At the same time, the history of the region provides inference into past interactions between terrestrial ecosystems and the atmosphere for CO_2, which is the largest carbon flux. This then provides a guide for thinking about the current state of CO_2 exchange and what the future might hold.

Widespread permafrost thaw at the end of the Last Glacial Maximum and into the warm early Holocene changed the distribution of terrestrial ecosystems including the formation of many thermokarst lakes (53, 54) as ice sheets retreated and ecosystems reorganized under this new climate. This initially resulted in a loss of permafrost carbon, which was exported into freshwater ecosystems (67), the ocean (68, 69), and the atmosphere (70, 71). Reorganizing ecosystems across the region eventually then began to absorb net CO_2 (72, 73), acting as a carbon sink over decades, centuries, and millennia where more carbon was retained within plant biomass and soil organic matter as compared to what was returned to the atmosphere (73–75). Tundra and boreal plant communities featuring long-lived perennials such as grass-like sedges, mosses, shrubs, and trees accumulated carbon in living biomass, with the regional vegetation biomass carbon pool fluctuating locally along with disturbances, ongoing deglaciation with isostatic adjustment of the land surface, as well as orbital shifts in Holocene climate (76), but at a much smaller scale than at the transition from the Late Glacial. Soils, however, continued to accumulate organic carbon in frozen and waterlogged conditions over centuries to millennia, including as widespread peatlands that expanded across formerly glaciated regions well into the Holocene (21, 72, 75, 77). The terrestrial soil carbon pool also fluctuated in size locally in response to disturbances and climate, but in general accumulated carbon far longer than the plant carbon pool. Consequently, terrestrial ecosystems across the whole region acted as a persistent net carbon sink toward the end of the preindustrial Holocene (71, 73, 75, 78).

Carbon sink: an ecosystem taking up and storing net carbon into vegetation and soils, usually over a season, year, or longer

In the modern period, human-induced climate change may have already shifted some ecosystems away from net carbon sinks toward carbon-neutral or carbon sources, where new carbon uptake by plants and deposition into soils was balanced or exceeded by carbon loss from microbial activity, lateral carbon exports, and other punctuated disturbances such as fires and abrupt thaw (79). Indeed, this has currently been observed in some but not all study sites (80–82); thus, it has been a challenge to determine the net ecosystem response across the circumpolar scale with various synthesis studies reaching different conclusions (62–64, 66). The circumpolar terrestrial region acting as a persistent net carbon source of CO_2 over years to decades would be a signal of departure from long-term patterns that served to accumulate and store permafrost carbon in the Arctic over the recent centuries to millennia.

Current observations of CO_2 exchange provide mixed evidence as to the state of carbon exchange for the northern high-latitude region (83). Atmospheric observations that integrate across large regions have indicated substantial changes in the seasonal cycle of high-latitude ecosystems across decades due to changing ecosystem carbon dynamics (84). Estimates of biospheric fluxes from models are used to constrain local ecosystem activity in combination with atmospheric transport models in order to interpret atmospheric concentration measurements from the relatively sparse flask network. These methods show the Arctic and boreal regions as an annual net carbon sink of 0.42 Pg $C\text{-}CO_2$ year^{-1} averaged over the past 40 years. Arctic regions (60–90°N) were responsible for almost one-third of this (0.13 Pg $C\text{-}CO_2$ year^{-1}) and remained relatively consistent over time, whereas the boreal region (50–60°N) has gradually increased its carbon sink strength (83). But resolving whether the region is acting as a carbon source or sink requires separating the larger background influence of increasing fossil fuel and biospheric fluxes arising from the midlatitudes, as well as predefining regional ecosystem activity with models (priors), both of which have an influence on the results.

Regional atmospheric measurement campaigns with aircraft help focus in on local influences (85), and a comprehensive three-year study showed the tundra region of Alaska to be a consistent net carbon source, whereas the boreal region of Alaska was either net carbon neutral or a CO_2 sink depending on year (86). The integrated Alaska region covered by this study was a net carbon source of 0.025 Pg $C\text{-}CO_2$ year^{-1} averaged across the three years. If this study area (1.6×10^6 km^2) was representative of the entire circumpolar permafrost soil area (17.8×10^6 km^2), this amount would be equivalent to a net carbon source of 0.3 Pg $C\text{-}CO_2$ year^{-1}. Upscaled eddy covariance tower measurements (80) and a separate remote sensing–based upscaling analysis supported this aircraft result in Alaska (87), and so this carbon source finding appears robust across the Alaska region using these measurement and scaling techniques. At the same time, this type of detailed evidence does not exist for other large permafrost regions, Siberia, for example, where similarly intensive aircraft campaigns have not yet been conducted.

FUTURE CARBON DIOXIDE EMISSIONS: SCENARIOS AND NARRATIVES

Supplemental Material >

Based on the range of projected Arctic carbon emission rates described in earlier sections, three example scenarios of low, medium, and high net CO_2 emissions that span this range can be envisioned over this century: 37, 74, and 149 Pg C-CO_2 cumulative release by the end of the century for the Arctic region (**Table 1**; **Supplemental Appendix**). Each scenario roughly doubles the net emissions of the previous scenario and together they span the range of estimates within the ensemble of projections (**Figure 5**). These example low, medium, and high scenarios are three points over a range of potential emissions and are meant to be significant to 5–10 Pg C. The specific cumulative releases are based on realistic increases in annual emission rates over a century and serve to illustrate the range of potential future pathways for the Arctic carbon cycle. These quantitative Arctic carbon emission scenarios are then coupled with sets of narratives, qualitative descriptions of changing ecosystem processes that are consistent with the annual and cumulative carbon emissions that comprise the scenarios (88). All of these scenarios have support from published projections and can be linked to specific patterns and processes on the landscape with the addition of the narratives. This scenarios-and-narratives approach is meant to help better represent the still-incomplete state of knowledge about future Arctic carbon emissions (1, 89) and complement more limited assessments of the permafrost carbon literature that present a narrower view (49).

Table 1 Low, medium, and high levels of net CO_2 and net additional CH_4 emissions to the atmosphere during 2000–2099, with associated narratives

Arctic carbon emission scenarios	2021 Annual emissions (Pg C year^{-1})	2049 Annual emissions (Pg C year^{-1})	2099 Annual emissions (Pg C year^{-1})	2000–2099 Cumulative emissions (Pg C)	Global warming scenario	Narrative
1. Low CO_2	0.332	0.374	0.449	37	RCP2.6	1. Low global and Arctic warming
					RCP4.5–RCP8.5	2. Slow plant and soil response in sync
					RCP4.5–RCP8.5	3. Fast plant and soil response in sync
2. Medium CO_2	0.344	0.736	1.436	74	RCP4.5–RCP8.5	1. Heightened soil response
					RCP4.5–RCP8.5	2. Reduced plant response
3. High CO_2	0.630	1.470	2.970	149	RCP8.5	1. High global and Arctic warming and fast ecosystem response
	(Tg C year^{-1})	(Tg C year^{-1})	(Tg C year^{-1})	(Tg C year^{-1})		
4. Low CH_4	5	11	21	1,090	RCP2.6–RCP4.5	1. Slow warming and slow ecosystem response
5. Medium CH_4	12	26	51	2,575	RCP4.5–RCP8.5	1. Moderate to high global and Arctic warming; moderate ecosystem and landscape response
6. High CH_4	22	50	100	5,050	RCP8.5	1. High global and Arctic warming; fast ecosystem and landscape response

An example low-range net CO_2 emissions scenario is a cumulative net release of 37 Pg C-CO_2 by the end of the century (**Table 1**). For this scenario, annual rates of net CO_2 emissions range from 0.33 Pg C-CO_2 year^{-1} in 2021, rising slowly to 0.45 Pg C-CO_2 year^{-1} by 2099 over the entire 17.8×10^6 km^2 permafrost soil region of the Arctic. These low emissions increases spread across the entire region would be very challenging to detect with the current atmospheric flask sampling network, which tries to distinguish these changes against a background atmosphere awash with fossil fuel CO_2 and the impacts of other biospheric changes mixing northwards from lower latitudes (83). At the ecosystem scale, this regional net CO_2 emission rate is equivalent to 16 g C-CO_2 m^{-2} at the beginning of the century and rises to 25 g C-CO_2 m^{-2} at the end of the century. These values are an average of the entire region and so would likely scale higher or lower with soil carbon density and plant biomass in any particular terrestrial ecosystem (87). Some ecosystems such as peatlands (90) could potentially even remain as net carbon sinks while the region as a whole was a carbon source in this scenario. At the ecosystem scale, these annual losses would also be difficult to detect with eddy covariance measurements against interannual variability or with direct measurements of plant and soil carbon pools given heterogeneity at the site. Over a decade or several, repeated measurements in the same ecosystem would start to detect these trends at the site scale, but upscaling ecosystem observations to the region would remain a challenge (91).

This low-range net CO_2 emission scenario could represent three types of future conditions with different narratives (**Table 1**). First, low-range net CO_2 emission could be a result of a trajectory of slower global and Arctic warming, such as described by RCP2.6 or related scenarios with significant mitigation of human carbon emissions that have the effect of limiting global temperature change to below 2°C. In this narrative, limited Arctic warming and permafrost thaw still lead to some permafrost soil carbon emissions outpacing increases in plant activity and growth, resulting in low cumulative net CO_2 emissions over the century timescale. Landscape disturbances such as wildfire remain similar to historic patterns for boreal and tundra ecosystems. A second different narrative that supports this same level of net CO_2 release is moderate to high global and Arctic warming (e.g., RCP4.5 to RCP8.5) but where the slow response of the ecosystem carbon cycle buffers these environmental changes. Here, permafrost soil carbon remains resistant to microbial decomposition even when thawed, partly because frozen carbon has previously undergone decades and centuries of decomposition (92, 93), it is protected by interactions with soil mineral surfaces, and/or newly thawed soil carbon may be waterlogged and still protected from rapid microbial breakdown by anaerobic conditions (94, 95). Changes in plant growth and biomass are also slow and do not match increases in soil emissions leading to overall net CO_2 release to the atmosphere. Wildfires are a trigger for rapid change; thus, in this narrative they again remain similar to historic patterns. The third narrative for this same net CO_2 emission scenario is on the other end of the ecosystem response spectrum. Under moderate to high levels of global and Arctic warming, high levels of plant growth and replenishment of soil organic matter compensate for much of what was released from decomposition of permafrost soils. In this fast ecosystem carbon cycle response narrative, plant colonization would be relatively rapid, and greening would be dominant with new shrub and tree communities replacing grass-like graminoid tundra that was previously widespread (96–99). This could occur directly due to warming temperatures and CO_2 fertilization, and disturbances by fire and abrupt thaw could also speed vegetation change and accumulation of new soil carbon from regrowing vegetation (100). The biomass carbon of larger-statured shrubs and trees compensates for soil carbon losses, even though those are also occurring at relatively high rates. In this fast ecosystem-change narrative, soils are losing old stored carbon rapidly (101) but much of this loss is compensated by plant uptake, leading to overall low net CO_2 emission. These three

Browning: consistent declines in vegetation productivity over decadal timescales, typically inferred from satellite remote sensing observations

narratives together illustrate that a single, low net CO_2 emission scenario for the Arctic could occur within future worlds that look very different from one another.

An example medium-range net CO_2 emission scenario of a cumulative 74 Pg C-CO_2 by the end of the century also has annual rates of 0.34 Pg C-CO_2 year^{-1} in 2021 but exceeds 1 Pg C-CO_2 year^{-1} by 2068 increasing to 1.4 Pg C-CO_2 year^{-1} by 2099 (**Table 1**). These rates are expected for medium or high global and Arctic warming, but not for low warming. Just as in the low net CO_2 emission scenario, the annual release is still only barely detectable at mid-century by the flask network, and it is not until 2070 when changes to the circumpolar atmospheric carbon cycle might be distinct from the larger biospheric and human changes happening in the midlatitudes. In this scenario, there are two narratives, both which feature large soil carbon losses. First, plant growth and greening may still be increasing across the region, with shrubs and trees encroaching into tundra previously dominated by grass-like graminoids. But this greener Arctic would be significantly overwhelmed by carbon losses arising from the thawing of permafrost ground and the decomposition of soil organic matter by microbes. This would be a result of direct temperature effects on microbial metabolism and organic matter decomposition, and would be accelerated by abrupt thaw disturbance events occurring frequently across the portion of the Arctic landscape that is susceptible (47). Abrupt thaw exposes much more permafrost carbon to microbial activity and also leads to large lateral losses of dissolved and particulate organic carbon into freshwater aquatic ecosystems where it is subject to breakdown by UV oxidation and microbes (102). A second narrative for medium-range cumulative net CO_2 emission has lower soil carbon loss, but the plant response is not as vigorous and thus leads to net CO_2 emissions. In this narrative, despite warmer conditions, a longer growing season, and CO_2 fertilization of photosynthesis, other stressors to plant growth such as drought conditions or soil waterlogging as a result of permafrost thaw and subsiding ground limit the potential growth of plants. Long-lived perennial plants find themselves increasingly occupying unsuitable microhabitats now that the environment has changed. Furthermore, succession and growth of new plants is slow and is limited by seed source and dispersal, and the surface soil organic layer that is inhospitable for new seedling establishment (103, 104). Ecosystems where plant growth was slowed or inhibited (browning) would be common within a mosaic with other regions where plants appear to be thriving (greening), depending on the local characteristics of the environment (105, 106). These two narratives, either favoring increased soil carbon losses or decreased plant uptake and growth, both result in medium-range CO_2 emissions, but the two future worlds would appear far different from each other.

The final example, a high-range net CO_2 emission scenario, is represented by a cumulative 149 Pg C-CO_2 by the end of the century, with annual emission rates of 0.63 Pg C-CO_2 year^{-1} in the year 2021 that escalate quickly, exceeding 1 Pg C-CO_2 year^{-1} by 2035 and reaching almost 3 Pg C-CO_2 year^{-1} by 2099 (**Table 1**). These conditions are expected only for high global and Arctic warming and become detectable at the ecosystem and regional level relatively rapidly within several decades. High emission rates are fueled by widespread thaw and permafrost carbon loss, with plant communities responding only slowly as the environmental and biological bottlenecks to succession limit growth and spread of new plant species that can tolerate the changed environmental conditions. Browning regions are equal to or more common than greening regions. Abrupt thaw features are common across many parts of the landscape, most commonly observed in their more subtle form of subsided ground surface where ground ice has melted. In fact, the entire land surface is subsiding, but because ground ice distribution is heterogeneous it is clear that subsidence is widespread. Amid the larger landscape of subsidence, hot spots of physical erosion are clearly visible as they expose deep permafrost to thaw and permafrost carbon to decompose while plants struggle to establish on the muddy and continuously eroding soil surfaces of lowlands, or the desiccated hardpans common to uplands (107). Wildfires are increasing in boreal ecosystems and have become commonplace in tundra as well. A single narrative of rapid change in the Arctic region, where plant growth and vegetation change cannot keep pace with increasing disturbance and soil carbon loss, leads to the high net CO_2 emission scenario.

METHANE EMISSIONS: OBSERVATIONS

Scenarios for CH_4 emissions in the Arctic have some important differences as compared to emissions of CO_2. Rather than historically acting as a net sink like CO_2, CH_4 has likely been emitted from Arctic wetlands and lakes at various rates since the Last Glacial Maximum through the transition to the Holocene, as a byproduct of anaerobic decomposition in lakes and wetlands (54, 108). Therefore, the net emission of CH_4 is not in itself necessarily a signal of change of current significance to the carbon cycle or climate. Instead, it is additional net CH_4 that causes current climate forcing, and this change must be detected both upon a backdrop of existing, preindustrial CH_4 emission rates as well as a global atmosphere that is filling with CH_4 from various human activities such as agriculture, natural gas production, etc., that are all widespread and increasing (83, 109).

Although northern ecosystems contribute to the global CH_4 budget, there is mixed evidence about the degree to which additional CH_4 from northern lakes, wetland ecosystems, and the shallow Arctic Ocean shelves is currently contributing to increasing atmospheric concentrations. Analyses of atmospheric CH_4 concentration time series in Alaska concluded that local ecosystems surrounding the observation site have not changed in the exchange of CH_4 from the 1980s until the present, but this analysis could be obscured by background changes of other northern wetland ecosystems, or increasing atmospheric CH_4 concentrations derived from midlatitudes sources (110). Also, this contrasts with indirect integrated estimates of CH_4 emissions from observations of expanding permafrost thaw lakes that suggest a release of an additional 1.6–5 Tg CH_4 year^{-1} over the past 60 years (111). At the same time, CH_4 fluxes at the ecosystem to regional scale may have been systematically underobserved, in part due to the low solubility of CH_4 in water leading to ebullition (bubbling) flux to the atmosphere that is heterogeneous in time and space (112). Other newer quantifications include cold-season CH_4 emissions that can be >50% of the annual budget of terrestrial ecosystems (113); geological CH_4 seeps that may be climate sensitive if permafrost currently serves as a cap preventing atmospheric release (114–116); and estimates of shallow Arctic Ocean shelf CH_4 emissions, where the range of estimates based on CH_4 concentrations in air and water has widened with more observations and now ranges from 3 Tg CH_4 year^{-1} (117) to 17 Tg CH_4 year^{-1} (118). Although these are important new studies, it is unclear to what extent these sources represent additional net CH_4 in the modern period, which would lead to additional climate forcing. Observations such as these highlight that source estimates for CH_4 made from atmospheric observations (119) are typically lower than CH_4 source estimates made from upscaling of ground observations, and this problem has not improved, even at the global scale, over several decades of research (120, 121).

FUTURE METHANE EMISSIONS: SCENARIOS AND NARRATIVES

Based on rates from projections reported earlier, three example scenarios of net CH_4 emissions were envisioned over this century: 1090, 2575, and 5050 Tg C-CH_4 cumulative release by 2099 (**Table 1**). It is important to recognize that these scenarios represent CH_4 added to the current emissions of roughly 20–60 Tg C-CH_4 year^{-1} from high latitude lakes and wetlands (122, 123). As with the CO_2 scenarios, each additional net CH_4 emission scenario roughly doubles the net additional emissions of the previous scenario, and together they span the range of projected estimates, allowing for the construction of a parallel set of narratives of Arctic carbon cycle change based on these annual and cumulative emissions.

In an example low-range additional net CH_4 emission scenario, rates in 2021 are 5 Tg C-CH_4 year^{-1} and thus are already slightly elevated at present compared to historical rates, given that the Arctic is already warmer today. These rates slowly increase, exceeding 10 Tg C-CH_4 year^{-1} in 2045 on the way to rates of 20.8 Tg C-CH_4 year^{-1} at the end of the century, roughly a 50% increase in preindustrial emission rates (**Table 1**). This leads to a cumulative release of 1,090 Tg C-CH_4 by the end of the century. These modest rates of CH_4 increases are likely to be primarily driven by direct temperature increases of microbial metabolic rates, the increase in organic carbon availability derived from thawing permafrost carbon, and potentially an increase in new carbon substrates to methanogenesis as a result of stimulated plant growth. This final process is not directly related to the release of stored permafrost soil carbon per se but does represent a world with additional net CH_4 release fueled directly and indirectly by climate warming. Lastly, increasing net CH_4 emissions could also represent expanding wetlands and lakes with permafrost thaw that increase the anaerobic ecosystem representation on the landscape.

The medium-range additional net CH_4 emission scenario features rates that are already climbing in the recent period, reaching 11.5 Tg C-CH_4 year^{-1} additional net CH_4 by 2021 and doubling the baseline preindustrial CH_4 emissions (20–60 Tg C-CH_4 year^{-1}) by 2078 (**Table 1**). Additional net CH_4 emissions would continue to increase in magnitude to 50.5 Tg C-CH_4 year^{-1} in 2099. This leads to a cumulative release of 2,575 Tg C-CH_4 by the end of the century. These rates of CH_4 increases would be supported by processes described in the previous scenario and would also be stimulated by widespread abrupt thaw that creates more lakes, wetlands, and anaerobic conditions as ground ice melts and the ground surface subsides. Increased subsea permafrost CH_4 emissions also contribute as ocean warming on the shallow Arctic shelves stimulates release from organic and inorganic subsea methane sources (124). Incomplete CH_4 consumption in the ocean water column allows for a proportion of these additional CH_4 emissions to reach the atmosphere (25).

The high-range additional net CH_4 emission scenario again features rates that are already climbing quickly in the recent period, reaching 22 Tg C-CH_4 year^{-1} additional net CH_4 already by 2021 (**Table 1**). Additional net emissions continue to increase thereafter, reaching 100 Tg C-CH_4 year^{-1} in 2099. This leads to a cumulative release of 5,050 Tg C-CH_4 by the end of the century. All of the processes stimulated in the medium-range scenario occur at higher rates while processes that could slow methane emissions to the atmosphere are overwhelmed. This high-end scenario is based on widespread abrupt thaw and wetting of the landscape, with wetlands and thaw lakes becoming even more abundant on the landscape, favoring anaerobic decomposition of newly thawed permafrost carbon (125). Geologic CH_4 emanating from deep in the Earth, previously capped by permafrost, now starts to leak out at higher rates through thaw lakes, undersea (126), and from CH_4 craters that destabilize as a result of thawing and thinning permafrost (127) (**Figure 6**). Low solubility of CH_4 in water allows these new sources to bubble CH_4 efficiently through the fresh and ocean water columns such that CH_4 oxidation is low and thus these new sources reach the atmosphere.

COMBINED IMPACT OF CARBON DIOXIDE AND METHANE EMISSIONS: SCENARIOS AND NARRATIVES

These three levels of low-, medium-, and high-range CO_2 and CH_4 emissions pair in nine scenarios that cover a range of climate warming impacts induced by Arctic carbon emissions (**Figure 7**). These scenarios represent the predominant mean projections across the suite of model projections reviewed earlier (**Figure 5**) but do not necessarily cover outlier estimates, which we discuss in the next section. Overall, CH_4 emissions by mass range from 0.9–11.9% of total carbon emissions

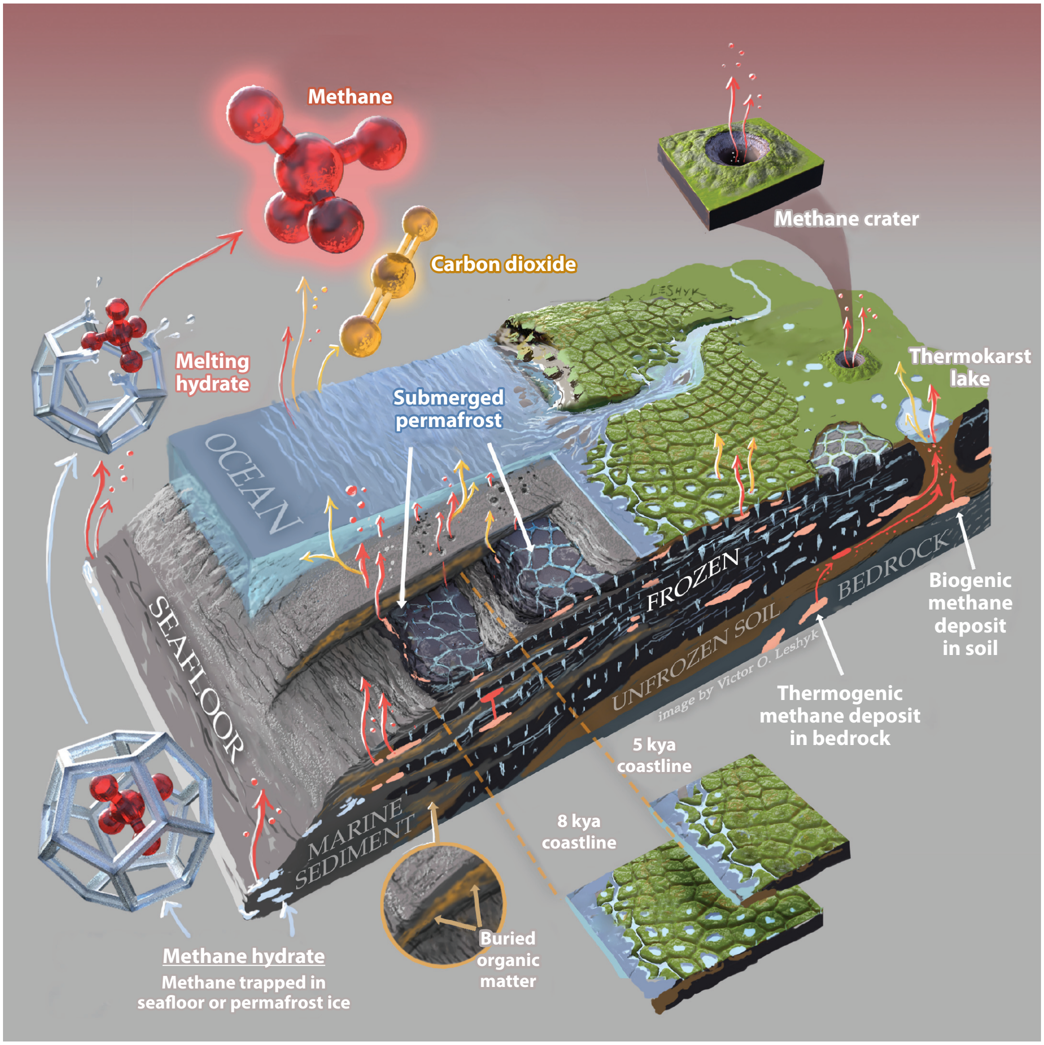

Figure 6

Subsea and geologic sources of carbon emissions. The shallow Arctic ocean shelves cover 2.5×10^6 km^2 that was formerly exposed as terrestrial ecosystems during the Last Glacial Maximum when sea level was 120 m lower than today. As sea level rose, these permafrost ecosystems were submerged and started to thaw. This would have exposed organic carbon in permafrost to decomposition and other processes that would release CO_2 and CH_4 together. Anaerobic ocean seafloor conditions favor the production and release of CH_4 and CO_2, but CH_4 is subject to oxidation in the water column by methanotrophs. As such, it would still reach the atmosphere as CO_2 unless ebullition (bubbling) bypassed oxidation. Methane as hydrates or as geologic seeps also could destabilize and enter the atmosphere either on the ocean shelves or as permafrost thins on land. Methane craters with elevated CH_4 levels have been recently observed and appear as a new phenomenon on the Arctic landscape. It is largely unknown how much ongoing permafrost thaw on the ocean shelves has already released CO_2 and CH_4 in the past and whether these emissions are increasing as a result of recent warming.

across the range of scenarios, with a mean of 4.2% and a median of 3.3%. The combined effect of CO_2 and CH_4 emissions is calculated by using the sustained global warming potential of CH_4 emissions as a multiplier to convert mass of carbon contained in CH_4 so that it can be directly compared with the climate effect of the carbon mass in CO_2 when reported as CO_2-equivalent (CO_2-e) (128, 129) (**Supplemental Appendix**). The importance of CH_4 emissions ranges from

Supplemental Material >

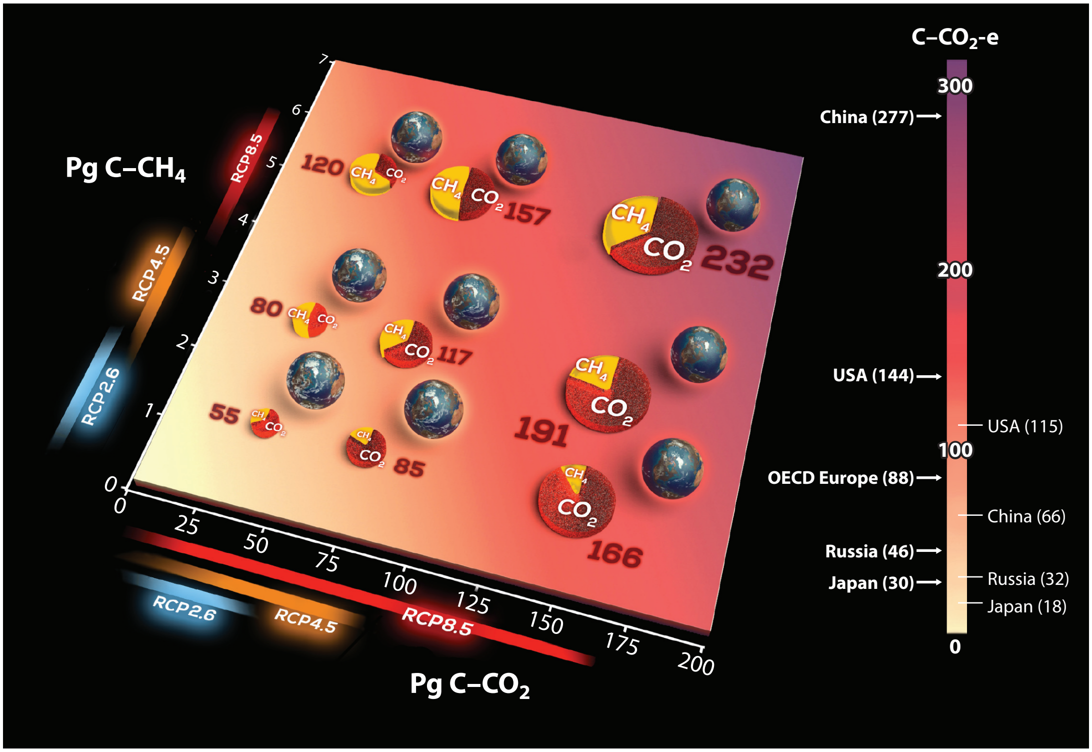

Figure 7

Nine example scenarios for cumulative projected greenhouse gas emissions based on three levels (low, medium, high) of net CO_2 and three levels (low, medium, high) of net CH_4 emissions to the atmosphere for 2000–2099. Axes represent mass of carbon (petagrams) contained in either CO_2 or CH_4 as a cumulative net release to the atmosphere in addition to preindustrial background carbon exchange. The color scale is the total greenhouse gas equivalents represented by the annual emissions of CO_2 and CH_4 together, in CO_2-equivalent (CO_2-e) units (petagrams C) with the weighting of CH_4 relative to CO_2. The CO_2-e unit is also compared to extrapolated 2019 country-level carbon emissions (*left labels*) and historic (1850–2021) country-level fossil fuel carbon emissions (*right labels*) for several representative nations. The size of each pie chart is equivalent to the total CO_2-e for each particular scenario; the cumulative CO_2-e labeled under each pie chart shows the relative contribution of CO_2 and CH_4 to the total CO_2-e. The nine scenarios for which emissions were quantified do not occupy the upper ends of the CO_2 and CH_4 emissions axes; a decade of projections has not eliminated the possibility of upper-end scenarios that are higher or lower than the range of those nine scenarios depicted here. Calculations here are also described in the **Supplemental Appendix** and **Table 1**.

Supplemental Material >

CO_2-equivalent (CO_2-e): unit of measurement that combines climate impact of carbon dioxide and methane into a comparable form

11% to 69% of total warming impact across the range of scenarios, with a mean of 37% and a median of 36%. One important feature of the total climate forcing based on rates of CO_2 and CH_4 emissions together is the relative effect of CO_2 compared to CH_4 emissions. Increasing emissions along the range of the CO_2 axis reaches significant levels of CO_2-e in the middle of the axis (when CH_4 emissions = 0), whereas this same level of CO_2-e is not reached until the upper end of the CH_4 emissions axis (when CO_2 emissions = 0). This suggests that anticipated Arctic carbon climate forcing caused by CO_2 cannot be overlooked even with the higher global warming potential of CH_4 (14, 95), and indeed represents the majority of the climate forcing in six of the nine scenarios.

At the same time, the suite of model projections reviewed earlier that attempted to include abrupt thaw all showed CH_4 to be important for overall climate forcing, making two if not three scenarios in the lower right of **Figure 7**, where CH_4 plays a smaller role, appear to be less plausible. Scenarios on the upper left corner of **Figure 7** featuring medium to high CH_4 release with low CO_2 release seem less plausible unless increased plant growth and uptake can compensate for large soil CO_2 loss implied with the high level of change of CH_4 emissions. This is because processes such as the thawing of permafrost carbon and overall landscape change that stimulate CH_4 emissions in general would also favor increased CO_2 release as well. But there is a trade-off between anaerobic environments that favor CH_4 emission versus aerobic environments that favor CO_2; this trade-off would suggest that high levels of both greenhouse gases together are somewhat unlikely, unless CH_4 was also stimulated from sources other than organic carbon, such as clathrates or pathways of geologic/fossil CH_4 opened to the atmosphere by thawing permafrost. Despite inherent connections between CO_2 and CH_4 emissions, it is still not possible to completely rule out any of these nine scenarios across the Arctic system as a whole, since there are mechanisms and plausible narratives to support all of these Arctic carbon emission scenarios in a future warmer world.

Future Arctic carbon emissions can also be compared relative to national-level emissions (130, 131) that are the focus of climate change mitigation conversations (**Figure 7**; **Supplemental Appendix**). This helps to place scenarios and narratives discussed in this review alongside policy conversations aimed at reducing national greenhouse gas emissions. Many of the modeled climate change trajectories where mitigation of human carbon emissions leads to various global temperature targets do not necessarily contain all of the detailed information for the Arctic carbon cycle as compared to the projections reviewed here. In this way, it can be helpful to view potential Arctic carbon emissions as the equivalent of an additional nation of carbon emissions that must be accounted for in order to reach specific temperature targets. The lowest of the nine scenarios has cumulative emissions (as CO_2-e) greater than 100 years of the current (2019) national emissions of Russia or equivalent of 100 years of the 2019 emissions from two Japans. This was the only scenario that contained a narrative where global temperature was held below 2°C (e.g., RCP2.6). The medium-range emission scenario for both CO_2 and CH_4 produces cumulative emissions in between 100 years of 2019 emissions for OECD (Organisation for Economic Co-operation and Development) Europe and 100 years of 2019 emissions for the United States. Medium-range estimates of Arctic carbon emissions could result from moderate climate emission mitigation policies that keep global warming below 3°C (e.g., RCP4.5). This global warming level most closely matches country emissions reduction pledges made for the Paris Climate Agreement, whereas the Arctic carbon emissions, if realized, would need to be accounted for in order to actually meet those temperature targets. The high-range Arctic carbon emission scenario for both CO_2 and CH_4 produces cumulative emissions equivalent to 100 years of 2019 emissions for OECD Europe and the United States combined, or just below 100 years of 2019 emissions for China. These Arctic carbon emissions would occur with little to no global climate mitigation policy and serve to significantly accelerate climate change.

Supplemental Material >

Of course, countries are attempting to reduce their own human carbon emissions and so actual future cumulative country emissions will depend on future progress and are not likely to be equal to 100 years of 2019 emissions as was used for comparison purposes. Furthermore, past cumulative country-level carbon emissions (1850–2021) change the rank order of countries, with the United States having released 115 Pg C-CO_2 at the top of those estimates and China approximately half of that at 66 Pg C-CO_2 (**Figure 7**). In summary, however, this comparison highlights that even at the low and medium levels of human greenhouse gas emissions, additional Arctic carbon will need to be accounted for in order to meet future temperature targets; a sole focus on country-level emissions alone without accounting for the changing Arctic is not likely to be enough. At the same time, reducing fossil fuel emissions from human activity remains the best way to also dampen the response of Arctic carbon emissions and to keep permafrost carbon frozen in the ground.

CARBON CYCLE SURPRISES

Black swan event: an outlier event with extreme impact that is explainable after the fact but not predictable in advance

The scenarios described in the previous section span the range of mean estimates across the suite of projections (**Figure 7**). They all are plausible and supported by numerous studies with different assumptions about the Arctic carbon cycle. But they do not cover outlier estimates, and after a decade and more of research on the topic of permafrost carbon (**Figure 2**), these high- and low-end estimates have not been completely eliminated. What are these possible black swan events and what might they look like in terms of Arctic carbon emissions? Answering this question can be aided by also ruling out outlier events that do not have support within the model projections. First, abrupt "methane bomb" releases of overwhelming levels (e.g., petagrams) of CH_4 emissions occurring over one to a few years (e.g., 132) do not seem to be supported by observations or projections. Observations of CH_4 emissions from previously unrecognized or poorly quantified Arctic sources were initially unclear whether or not they represented additional net CH_4 in the modern period, and thus gave rise to the idea of this type of outlier event. At the same time, a slow leaking of additional CH_4 and CO_2 over decades and centuries still is projected to have a significant climate impact and remains perhaps equally insidious if additional greenhouse gases leak into the atmosphere largely unseen and unquantified by society. The recent appearance of "craters" with high concentrations of CH_4 in some parts of Siberia have raised new questions (133). This phenomenon is a surprise to the permafrost community and appears to be connected with potential CH_4 emissions. Each crater does not contain exceptional levels of CH_4 but could represent new pathways from deep fossil methane that have previously been capped by permafrost. Sources of geologic methane have been observed where ice and permafrost are retreating (116), including subsea (25, 134), and could be new sources to the atmosphere at levels that are only poorly constrained by the projections synthesized in this review.

A separate black swan issue for CH_4 emissions is the possibility of widespread drying of the Arctic landscape. Most of the model projections and all of the scenarios described in this review feature additional net CH_4 emissions that are higher than preindustrial levels. At the same time, the predictability of future Arctic surface hydrology remains uncertain (135), with ESMs suggesting widespread drying of soils even in the face of an accelerated hydrologic cycle overall but with individual models projecting widely divergent futures (34). A unique feature of Arctic ecosystems is that permafrost acts as a barrier to downward or lateral movement of water, where perched water near the surface is accessible by plants, microbes, and other organisms (136). Indeed, the Arctic has more wetland and lakes as compared to other latitudes as a direct result of permafrost (137). Although most studies projected lakes and wetlands expanding on a net basis in the warming future, there are also widespread observations of lakes draining as a result of permafrost thaw (46). If net draining was to occur across the Arctic landscape this could reduce CH_4 emissions below preindustrial levels, which is a future not represented in the nine scenarios described previously. At the same time, if microbially generated CH_4 emissions decreased with widespread permafrost thaw, that would be accompanied by increased CO_2 emissions due to an increase in thawed permafrost carbon experiencing aerobic conditions. As a result, the impact on climate could potentially still be substantial, and other geologic CH_4 sources could still be enhanced at the level of permafrost thaw that would produce a drier Arctic landscape and compensate for decreases in microbially generated CH_4.

A black swan event for net CO_2 emissions involves the response of tundra and boreal plant communities. Most if not all projections reviewed here either maintain or increase carbon stored in plant biomass and show increases in new carbon entering the soil pool as a result of mechanisms described earlier. However, other scenarios of boreal forest dieback have been identified in the literature (138). Changes in climate may exceed the tolerance of the current plant species pool in tundra and boreal forest, leading to widespread plant mortality (139). Limits to seed dispersal and establishment may prove to be a bottleneck that could last many decades or even centuries as vegetation communities respond to changes in climate (104). If plant carbon uptake was reduced for long time periods, this would tend to favor scenarios with high net CO_2 release as plants could not compensate for soil carbon losses. This effect may stay within the range of the scenarios presented here, but in the case of widespread dieback it could lead to even higher levels of CO_2 emissions than described by our high-range CO_2 scenario. The other end of this outlier effect is a thriving plant community with new carbon gains that completely offset all soil carbon losses and even lead the Arctic to gain net carbon. These scenarios are projected by some of the ESM projections, at least for this century, before soil carbon losses reverse this in future centuries (30). If the greening response of the plant community did continue for centuries, this would help alleviate the climate change impact of a changing Arctic, albeit it would be a very different place with different ecosystem types from the one we know today.

Vegetation change interacts with disturbances, with fire being one of the largest and best quantified. Fire has been a regular part of the boreal landscape and is increasing in some boreal and tundra areas (140, 141). Fire is included in some but not many of the projections that were used in scenario development, and the potential for fire to amplify abrupt thaw is a wildcard. Combustion of the soil organic layer exposes permafrost to thaw and increases the likelihood of abrupt thaw events to occur following disturbance by wildfire (142). Together these are likely to amplify permafrost carbon releases in ways that are challenging to quantify and likely are at the high end of our scenarios of carbon release or beyond.

In sum, the scenarios presented in this manuscript capture the range of mean Arctic carbon emissions as described in the scientific literature that may be expected in a warmer world. At the same time, the Earth system is currently headed toward a new climate state and may very well include Arctic carbon cycle surprises as described in the final section. What is hopefully clear is that reducing human carbon emissions as fast as possible will reduce change in the Arctic and remains the most obvious way to keep permafrost carbon frozen in the ground.

SUMMARY POINTS

1. Factors that control Arctic terrestrial carbon storage are changing. Surface air temperature change is amplified in the Arctic regions, where temperature rise has been approximately 2–3 times faster than the global average increase. Permafrost temperatures have been increasing over the past 40 years and now are at record high temperatures. Disturbance by fire (particularly fire frequency and extreme fire years) is higher now than in the middle of the past century.
2. Soils in the northern circumpolar permafrost region store 1,460 to 1,600 petagrams of organic carbon (Pg C), almost twice the amount contained in the atmosphere and approximately an order of magnitude more carbon than contained in plant biomass (55 Pg C), woody debris (16 Pg C), and litter (29 Pg C) in the boreal and tundra biomes combined. This large permafrost region soil carbon pool has accumulated over hundreds to thousands of years. There is an additional ∼960 Pg C in subsea permafrost and regions of deep sediments that are present but not well quantified, and 36 Pg C in permafrost outside of the Arctic region in Northern China and the Qinghai-Tibet Plateau.
3. Abrupt thaw represents a threshold change that degrades permafrost significantly faster than gradual top-down warming alone. A sizeable fraction (20%) of the Arctic landscape has high ground ice content and is susceptible to abrupt thaw with warming. This same

landscape fraction contains at least 50% of the surface permafrost carbon pool. Abrupt thaw not only degrades permafrost but also changes the distribution of upland and lowland ecosystem types with effects on both CO_2 and CH_4 emissions. Over longer timescales, the greenhouse gas equivalent of additional CO_2 and CH_4 emissions from abrupt thaw can add another 40% to projections of carbon release by top-down gradual thaw.

4. Based on published projections across a range of techniques, three levels of CO_2 and CH_4 emissions (low, medium, high) that are plausible outcomes of a warming Arctic combine together into nine scenarios of cumulative additional net greenhouse gas emissions by 2100. The CO_2-equivalent cumulative greenhouse gas emissions in these scenarios, which directly combine the effect of CO_2 and the higher warming potential of CH_4, range from 55 Pg C-CO_2-e to 232 Pg C-CO_2-e. In comparison, the 2019 emissions of Russia, OECD Europe, United States, and China, each scaled to 100 years, are 46, 88, 144, and 277 Pg C-CO_2, respectively. The historic (1850–2021) cumulative release of fossil fuel carbon for Russia, Japan, United States, and China was 32, 18, 115, and 66 Pg C-CO_2, respectively.
5. The idea of an abrupt "methane bomb" release of overwhelming levels (petagrams) of CH_4 emissions occurring over one to a few years is not supported by current observations or projections. At the same time, the recent appearance of methane craters, a new phenomenon associated with elevated CH_4 concentrations, is a reminder that Arctic carbon cycle surprises are likely to emerge as the Earth warms.

FUTURE ISSUES

1. Deep carbon pools remain poorly quantified in several parts of the northern circumpolar permafrost region, including deep sediments outside of the Yedoma region of Siberia and Alaska and in subsea permafrost on the shallow Arctic ocean shelves.
2. Subsea permafrost has been progressively submerged as sea level has risen ∼120 m from the Last Glacial Maximum to the present warmer Holocene. During this time, submerged permafrost has been thawing and carbon from these formerly terrestrial ecosystems and landscapes has had the potential to be lost. Determining the rate at which modern global warming is stimulating new greenhouse gas emissions, in addition to those caused by past ocean incursion of the Arctic ocean shallow shelves, remains important.
3. Improved methods are needed for detecting regional change in ecosystem greenhouse gas emissions against a background atmosphere that has increasing carbon dioxide and methane emissions as a result of human activities globally.
4. Standardizing a set of observational benchmarks of permafrost ecosystem dynamics that can be used for future modeling studies can help to set performance metrics against which various modeling approaches can be compared.
5. Microbial communities are the organisms largely responsible for CO_2 and CH_4 emissions from permafrost carbon. Connecting the identity of these organisms to ecosystem- and regional-scale emission rates may help to improve carbon cycle model projections.

DISCLOSURE STATEMENT

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