

# Arctic Terrestrial Carbon Cycling

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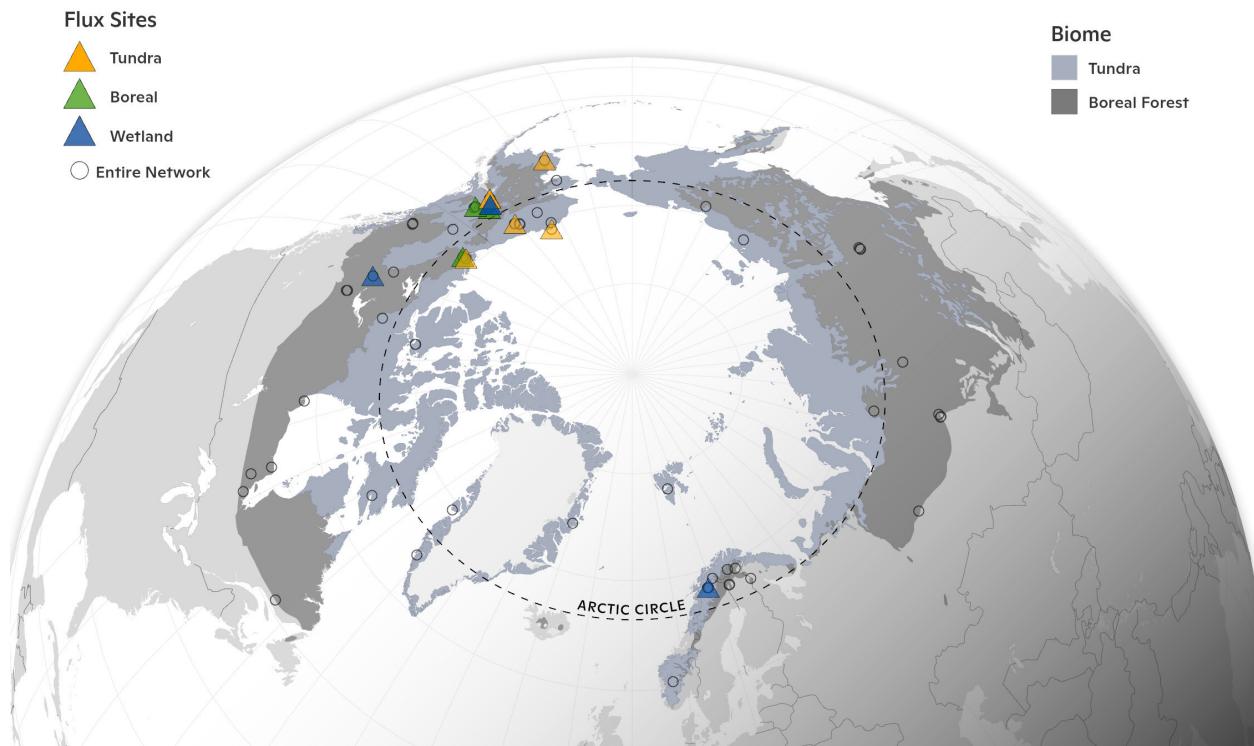
## Headlines

- When including wildfire emissions, the Arctic tundra region has shifted to a carbon dioxide (CO<sub>2</sub>) source and is a consistent methane (CH<sub>4</sub>) source.
- In 2024, permafrost temperatures were the highest on record at nearly half of Alaska long-term monitoring stations. On average, the year represented the second-warmest permafrost temperatures on record for Alaska.
- Wildfires in North American permafrost regions have increased since the mid-20th century, and circumpolar wildfire emissions have averaged 207 teragrams of carbon (Tg C) per year since 2003. 2024 was the second highest year for wildfire emissions north of the Arctic Circle.

## Introduction

The terrestrial Arctic region has been a carbon sink for thousands of years, meaning that there has been a net removal of carbon dioxide (CO<sub>2</sub>) from the atmosphere by plants and storage as organic carbon in soils and permafrost (perennially frozen ground). Climate warming can stimulate plant productivity and growth (see essay [Tundra Greenness](#)), resulting in enhanced rates of CO<sub>2</sub> removal from the atmosphere. At least 1.4 to 1.6 trillion tonnes of carbon (Hugelius et al. 2014; Schuur et al. 2022) have accumulated in terrestrial soils and permafrost across the region. Despite increased plant growth and CO<sub>2</sub> uptake, recent indicators suggest that some locations in the Arctic are becoming a net source of carbon to the atmosphere. Increasing surface air temperatures (see essay [Surface Air Temperature](#)) are causing permafrost to warm and thaw (Smith et al. 2024). Once thawed, permafrost carbon can be decomposed by microbes and released into the atmosphere as greenhouse gasses, CO<sub>2</sub> and methane (CH<sub>4</sub>). In addition to changes in plant and microbial processing of carbon, disturbances, such as wildfire, are resulting in pulse releases of CO<sub>2</sub> and CH<sub>4</sub> that may shift the Arctic from a net carbon sink to a source.

Here, we describe trends in permafrost temperatures, wildfire, and carbon cycling (CO<sub>2</sub> and CH<sub>4</sub>) at select long-term terrestrial monitoring sites and across the Arctic. Our discussion of the Arctic region considers all tundra and boreal lands within the northern permafrost region (Brown et al. 2002; Fig. 1), which covers  $16.6 \times 10^6$  km<sup>2</sup>.

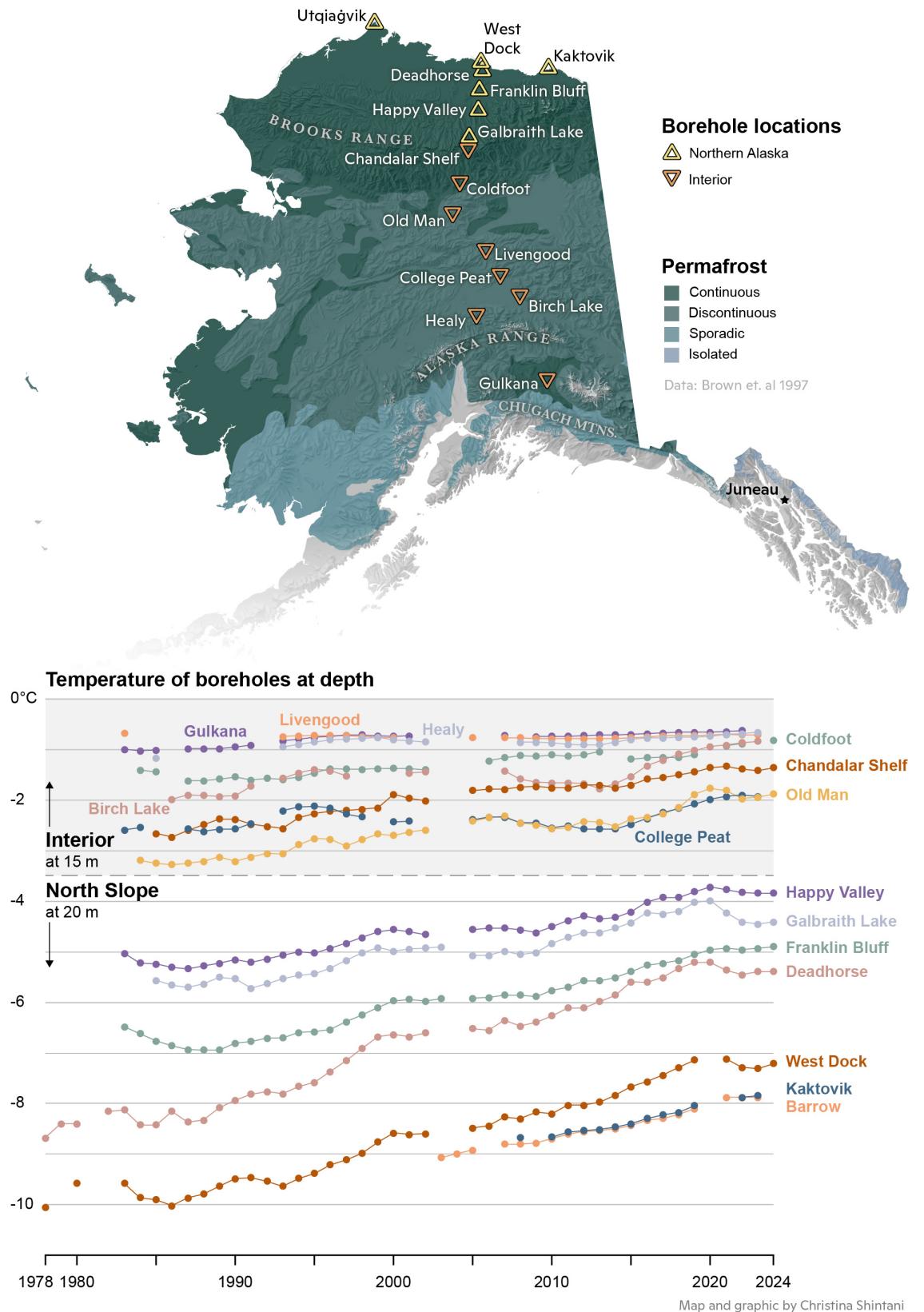


**Fig. 1.** The Arctic study domain for this essay includes all tundra and boreal biome regions within the northern permafrost region (shaded areas). Shaded triangle symbols represent a subset of Arctic carbon flux monitoring sites (open circles) that were included in the site-level analysis.

## Permafrost temperature trends

Permafrost temperatures have been monitored across the Arctic for almost half a century, providing a long-term record of climate change impacts. Deeper permafrost temperatures ( $\geq 15$  m), which are reported here, are less sensitive to seasonal temperature fluctuations than surface measurements, and thus, these long-term trends are good indicators of permafrost response to climate change. Here, we report trends in deep permafrost temperatures across Alaska, which, similar to permafrost temperatures across the Arctic, have been increasing for the past several decades (Smith et al. 2024). These warming trends are also associated with a deepening of the seasonally thawed soils, which can have important implications for carbon cycling.

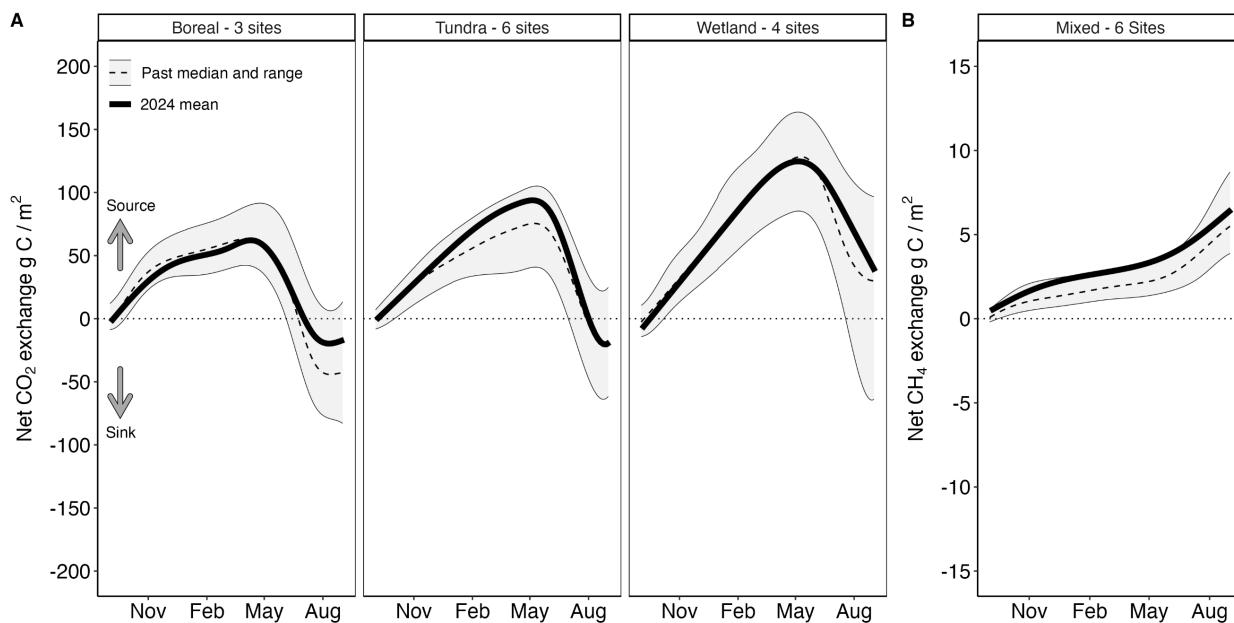
Permafrost temperatures in 2024 were the highest on record at 9 of 20 long-term monitoring sites across Alaska. Over the past four decades, the average increase in permafrost temperature ranged from 0.3 to 0.7°C per decade in colder permafrost in Northern Alaska (i.e., North Slope) and from 0.02 to 0.3°C per decade in warmer permafrost in Interior Alaska (Fig. 2). Greater permafrost warming rates at higher latitudes compared to lower latitudes are partly due to greater air temperature increases at higher latitudes. Additionally, permafrost with temperatures close to 0°C—such as those in lower latitudes in Interior Alaska—require energy (i.e., latent heat) to melt ground ice before temperatures can continue rising, bringing about reduced permafrost warming rates.



**Fig. 2.** Mean annual ground temperature (°C) at depths of 15 m (Interior Alaska) or 20 m (North Slope) below the surface at measurement sites across Alaska. (Figure prepared by Christina Shintani).

## Site-level carbon fluxes

Published observations from several long-term carbon flux monitoring sites have shown that some ecosystems have already shifted from carbon sinks to carbon sources (Schuur et al. 2021; Euskirchen et al. 2024). Here, we report net CO<sub>2</sub> and CH<sub>4</sub> exchange between ecosystems and the atmosphere through August 2024 for 13 locations (Fig. 1) in the North American and European permafrost region, each having between 6 and 17 years of data (Fig. 3). It is important to note that the fluxes from these sites do not directly correspond to the average fluxes for the entire biomes they fall within or the region as a whole. For the 12-month period of September 2023 to August 2024, the three boreal forest sites were on average a net sink of CO<sub>2</sub>, taking up 17 g CO<sub>2</sub>-C/m<sup>2</sup>/y from the atmosphere, which was slightly less CO<sub>2</sub> uptake than their long-term average. During the same 12-month period, the six tundra sites took up an average of 19 g CO<sub>2</sub>-C/m<sup>2</sup>/y, which was similar to their long-term average uptake. The four wetland sites were stronger CO<sub>2</sub> sources than in previous years, releasing an average of 46 g CO<sub>2</sub>-C/m<sup>2</sup>/y; however, larger data compilations demonstrate wetlands to be on average CO<sub>2</sub> sinks (Ramage et al. 2024). The six sites that measured CH<sub>4</sub> fluxes (three wetland, two tundra, one boreal forest) were on average net emitters of CH<sub>4</sub> (7 g CH<sub>4</sub>-C/m<sup>2</sup>/y) during this period. Fire, logging, and other disturbances at the regional scale, which may cause these biomes to become net carbon sources, are not included in these site-level assessments.



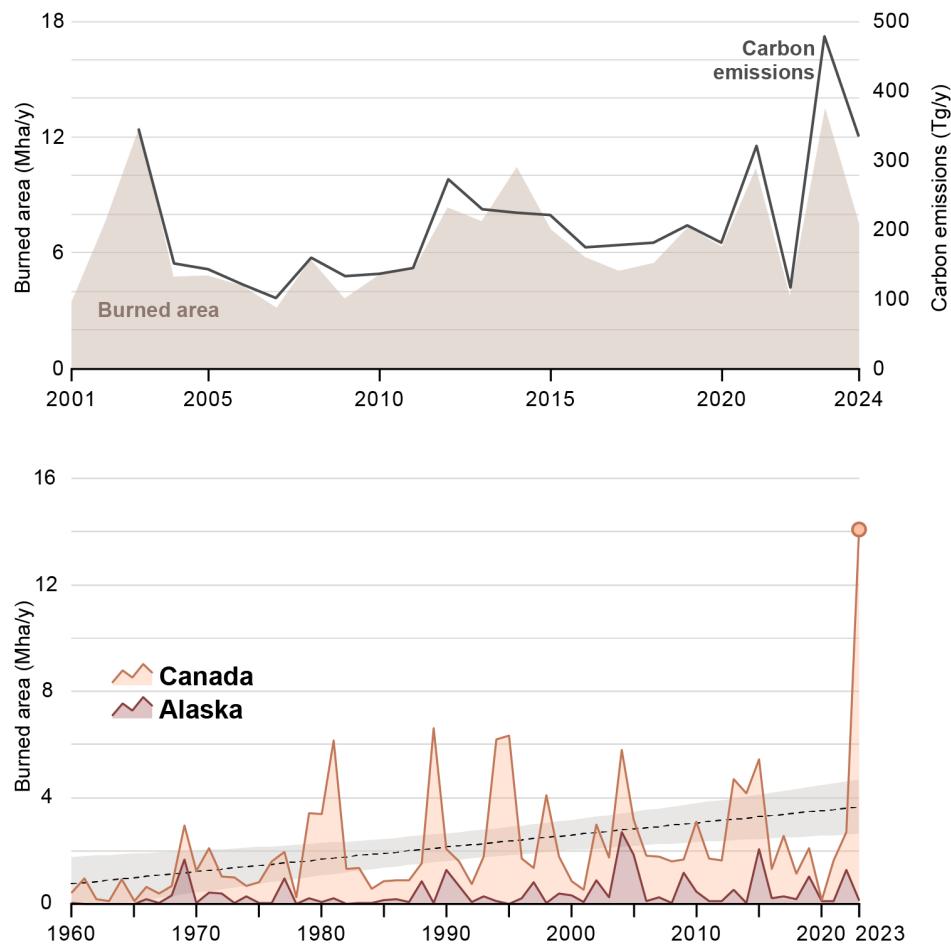
**Fig. 3.** (A) Cumulative net CO<sub>2</sub> exchange for 2024 (solid line) and previous years (shading; data records range from 6-17 years depending on site) across 13 North American and European eddy covariance sites. (B) Cumulative net CH<sub>4</sub> exchange for six eddy covariance sites (3 wetland, 2 tundra, 1 boreal forest). Positive values indicate a flux from the land to the atmosphere (carbon source) and negative values indicate a flux from the atmosphere to the land (carbon sink).

## Wildfire

Climate change has been intensifying high-latitude fire regimes, resulting in increased burned area, fire intensity, and carbon emissions. Vegetation regrowth after wildfire often re-sequesters CO<sub>2</sub> from the atmosphere over decades following fire, but more frequent and severe fires, combustion of below-

ground carbon, and long-term impacts of fire on ground thaw from combustion of vegetation and organic soils are resulting in net carbon emissions to the atmosphere over large spatial scales.

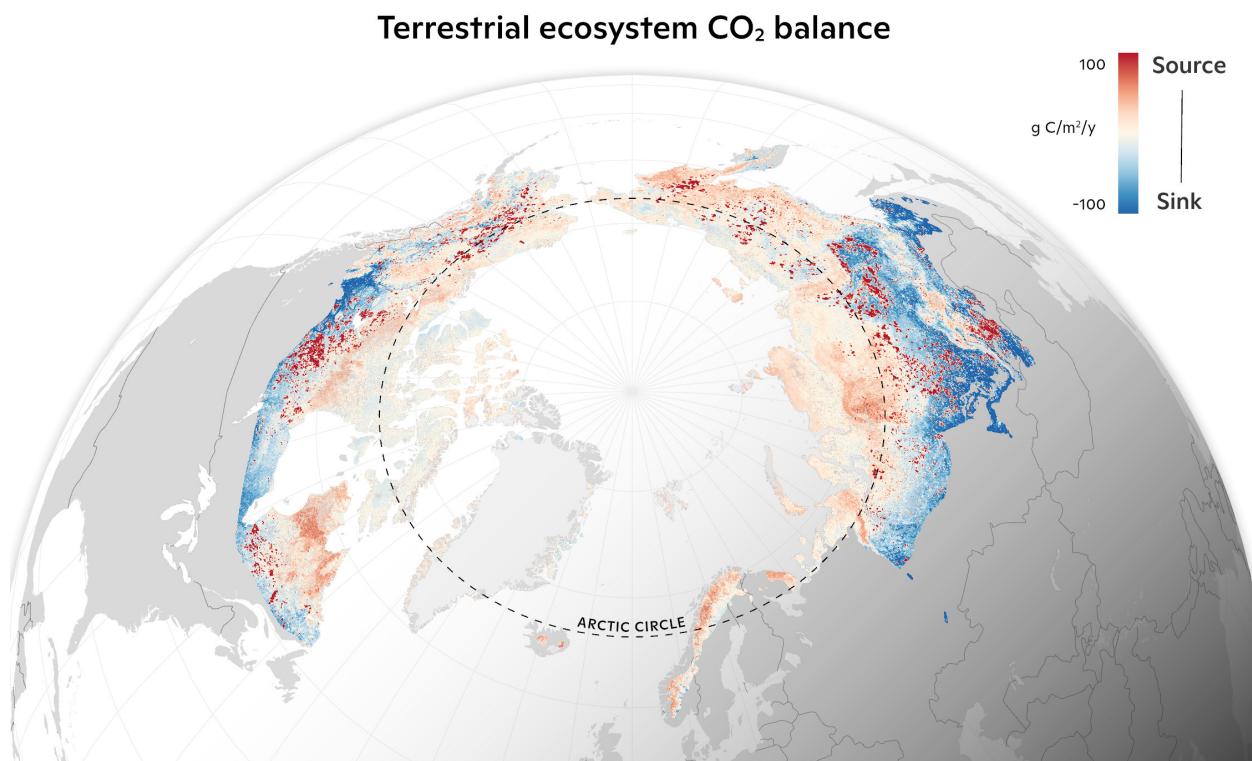
Given the high interannual variability in permafrost-region fires, it is not possible to detect trends across the entire Arctic (Fig. 1) over the previous two decades alone, which is when robust satellite-based fire products are available (Fig. 4, top panel). During this period, the largest carbon emissions from fire occurred in 2003 (343 Tg C) and 2023 (478 Tg C) due to large fires in southern Siberia and Canada, respectively. Fires in Canada's permafrost region in 2023 burned more than twice the area of any previous year on record and emitted 381 Tg C. Over a longer multi-decadal time frame, Alaskan and Canadian permafrost regions have experienced a clear upward trend in burned area since the mid-20th century (Fig. 4, bottom panel); burned area over the last 20 years (2004-23) is 28% higher than the 1981-2000 average and 62% higher than the 1971-90 average. Fire emissions have also been increasing at higher rates north of the Arctic Circle compared to permafrost regions below the Arctic Circle. North of the Arctic Circle the three years with the largest fire emissions during the last 20 years are 2019 (39.2 Tg C), 2024 (42.3 Tg C), and 2020 (60.5 Tg C). Across the entire pan-Arctic permafrost region, 2024 was a moderately high fire year, with 7.5 Mha burned and 335 Tg C emitted (Scholten et al. 2024; Copernicus Atmosphere Monitoring Service 2022).



**Fig. 4.** Burned area (2001-24) and direct fire carbon emissions (2003-24) across the circumpolar permafrost domain (top) and burned area (1960-2023) across the permafrost region within Alaska and Canada (bottom). Bottom panel shows an ordinary least squares regression line and 95% confidence intervals. Note that separate data products were used for burned area and emissions, and for the two time periods presented, as described in the [Methods and data](#) section.

## Regional carbon cycling trends

Across the Arctic region (Fig. 1), warmer temperatures over the past two decades (see essay [Surface Air Temperature](#)) were associated with more CO<sub>2</sub> uptake during the growing season (Virkkala et al. 2024a, 2024b), but CO<sub>2</sub> emitted from microbial respiration during the non-growing season offset growing season uptake (See et al. 2024; Virkkala et al. 2024a, 2024b). The pan-Arctic region was CO<sub>2</sub> neutral during 2001-20 (budget:  $-24 \pm 123$  Tg C/yr; Virkkala et al. 2024a, 2024b) when considering net ecosystem exchange (i.e., plant CO<sub>2</sub> uptake through photosynthesis and plant and microbial CO<sub>2</sub> release through respiration) and fire. However, the tundra region has shifted from a CO<sub>2</sub> sink—which it has been for millenia—to a small CO<sub>2</sub> source, while the boreal region remains a CO<sub>2</sub> sink (Hugelius et al. 2024; Ramage et al. 2024; Virkkala et al. 2024a; Fig. 5). The permafrost region is a CH<sub>4</sub> source, releasing 15 to 39 Tg CH<sub>4</sub>-C/yr during 2000-20 (Hugelius et al. 2024).



**Fig. 5.** Terrestrial ecosystem CO<sub>2</sub> fluxes with direct fire emissions (red shading) for the northern permafrost region (2002-20 average), showing areas that are CO<sub>2</sub> sources in pink and red and CO<sub>2</sub> sinks in blue. (Figure data from Virkkala et al. 2024b).

## Methods and data

Site-level carbon fluxes were measured using the eddy covariance technique and gap-filled using Marginal Distribution Sampling or Random Forest methods (e.g., Euskirchen et al. 2024). Data were acquired through 31 August 2024 from public databases and site principal investigators (Lundin et al. 2024; NEON 2024). The shading in Fig. 3 denotes the 2.5%, 50%, and 97.5% quantiles of previous years' data and were generated using a generalized additive model. The long-term (6-17 year) mean fluxes were calculated using a linear mixed effect regression model with land cover as the fixed effect and site as the random intercept.

Burned area data from 2001-24 were taken from the MODIS-based MCD64A1 product (Giglio et al. 2018), and fire carbon emissions from 2003-24 were derived from the Copernicus Atmosphere Monitoring Service (2022). Due to lags in data latency, we used burned area information from the VIIRS active fire-based product (Scholten et al. 2024) for the months of August, September, and October in 2024. Data for 2024 were updated as of 15 October 2024 for both fire emissions and burned area. We also provide information on longer-term patterns in burned area in North America's permafrost region using the Canadian National Fire Database (Stocks et al. 2002; Canadian Forest Service 2021) and the Alaska Large Fire Database (Kasischke et al. 2002; Alaska Interagency Coordination Center 2024). Note these data sources are less reliable during the earlier decades.

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