Carbon emissions from the 2023 Canadian wildfires

Abstract:

The size and intensity of the Canadian forest fires in 2023 have been quite high, with more

Compared to the preceding four decades, the average yearly area burned was more than seven times1. Here, we use inverse modeling using satellite carbon monoxide measurements to estimate the carbon emissions from these fires from May to September 2023. We discover that the amount of carbon emissions is 647 TgC (570–727 TgC), which is similar to the yearly emissions of fossil fuels from major countries; the United States, China, and India are the only ones that emit more carbon annually2.

We discover that the main cause of the fire's spread was the widespread hot, dry weather, with 2023 being the warmest and driest year since at least 19803. Despite the exceptionally high temperatures compared to historical records, climate projections indicate that even under a moderate scenario of climate mitigation (shared socioeconomic pathway, SSP 2-4.5), these temperatures are expected to be average for the 2050s.These circumstances may lead to a rise in fire activity and a reduction in the amount of carbon absorbed by Canadian forests, raising questions about the forests' capacity to store carbon over the long run.

Introduction:

Approximately 362 million hectares (ref. 9) of forest cover, or 8.5% of the world's total wooded area, are found in Canada10. By removing fossil carbon dioxide (CO2) from the atmosphere, these forests play a significant role as carbon sinks, slowing the rate of global warming11,12. But as a result of increased forest fire activity brought on by climate change, these forests' ability to absorb carbon is being suppressed13. 2023 has seen extremely large-scale forest fires, despite the fact that fires have become increasingly common.

2023 saw more than seven times (8σ) the average burned area over the preceding 40 years (1983–2022 mean, 2.2 million ha; range, 0.2–7.1 million ha) with 15 million hectares of Canadian woods burned (about 4% of the total forest area).

In 2023, the average burned area was more than seven times (8σ) that of the preceding forty years (1983–2022 mean, 2.2 million ha; range, 0.2–7.1 million ha)1. The negative effects of these fires on society are evident: millions are affected by poor air quality and 232,000 evacuations14. The carbon emissions resulting from the fire incidents are yet unknown, though. In this work, we use inverse modeling of carbon monoxide (CO) measurements from satellites to quantify these emissions. Next, we look at the predicted shifts in the frequency of hot, dry weather under climate change, together with associated climatic anomalies. We conclude by talking about how fires affect Canada's carbon budget.

Fire emissions:

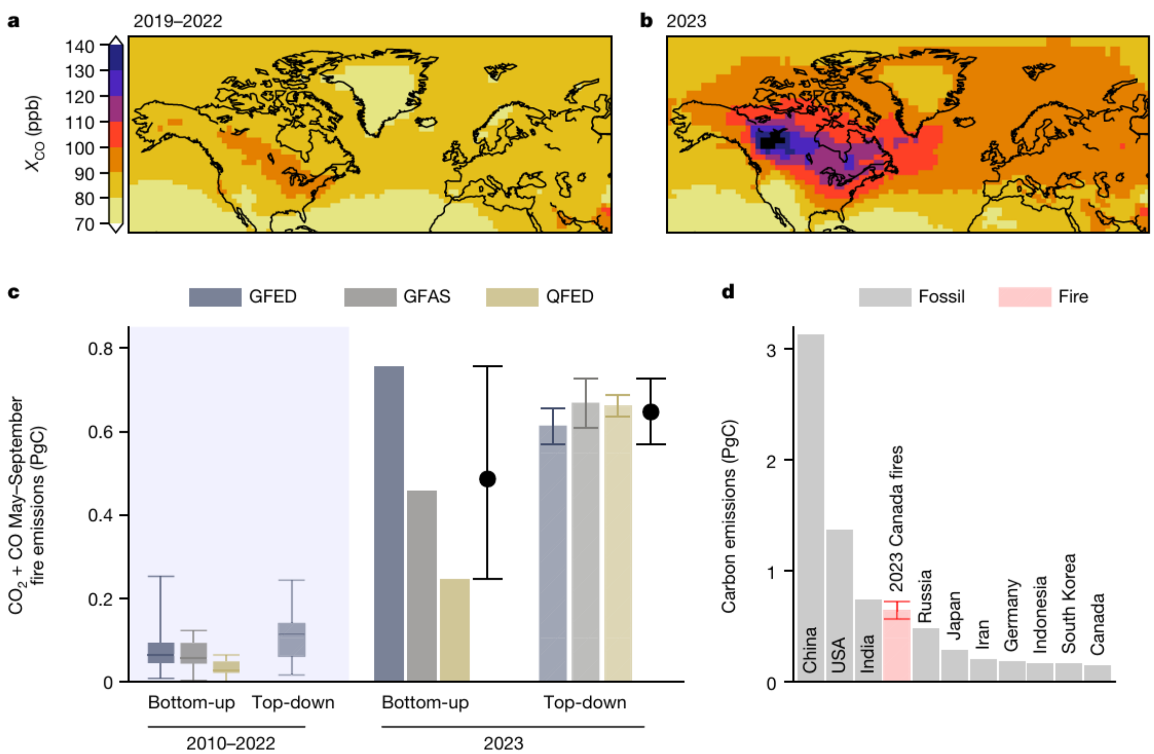
Top-down and bottom-up methods can be used to track fire carbon emissions from space. Bottom-up methods, such as burned area15 or fire radiative power16, track fire activity using satellite measurements. The estimations of fire activity are then combined with data like fuel loads and emission factors to estimate emissions of CO2, CO, and other trace gases. Global and regional estimates of trace gas and aerosol emissions might differ greatly from inventory, despite the fact that these bottom-up estimates are always getting better15,17.

Through the appropriate scaling of emission estimates to match the observed quantities of trace gases in fire plumes, top-down techniques offer a way to improve bottom-up estimates of trace gas emissions. This method's ability to incorporate emissions from both blazing .

Based on observational constraints from the space-based CO retrievals of the TROPOspheric monitoring instrument (TROPOMI), we estimate CO emissions from the 2023 Canadian fires top-down in this work (Fig. 1a,b). Three distinct bottom-up fire emission inventories are used to make these estimates: the rapid fire emissions dataset v.2.6r1 (QFED)18, the global fire emissions data base (GFED4.1s)15, and the global fire assimilation system v.1.2 (GFAS)16.

The CO2 /CO emission factors from the same bottom-up database are then used to determine the total carbon emissions emitted as CO and CO2 (CO2 + CO) for each inversion. The study is made more unclear by the possibility of significant variation in the CO2/CO emission ratios. We have included some of this uncertainty because the mean emission ratios for Canadian forests vary between each bottom-up database (range: 7.7–10.8 gC of CO2 per gC of CO2). The techniques section contains information on these inversions, and Supplementary Information sections 1 and 2 provide an explanation of the inversion results and an assessment of the top-down estimates' performance.

We discover that the top-down estimates are sensitive to prescribed hydroxyl radical (OH) abundances19, which control the atmospheric lifetime of the CO emitted, but they are relatively insensitive to decisions about inversion configuration (Supplementary Information section 1 and Supplementary Fig. 1).



CO enhancements and fire emission estimates are shown in Fig. 1. A–C, May–September TROPOMI CO (XCO) dry-air mole fractions

(a) averaged for the years 2019–2022 and for 2023 (b) totaled to a 2° × 2.5° grid. c, carbon emissions from Canadian forest fires (from carbon dioxide and carbon) for the May–September fire season of 2023, in contrast to fire emissions from 2010 to 2022 (box-and-whisker plots illustrate the distribution).

The top-down and bottom-up carbon emissions from fires from May to September of 2023 are depicted in Figure 1c. With a mean of 469 TgC, the bottom-up datasets exhibit significant variations, ranging from 234 to 735 TgC.

The top-down estimates (570–727 TgC) yield a greater mean estimate of 647 TgC and lower this range by 69%. With average emissions from 2010 to 2022 of 29–82 TgC for bottom-up inventories and 121 TgC for top-down estimates, emissions throughout 2023 will substantially exceed those from typical Canadian forest fires (Supplementary Fig. 2). We compare the top-down estimates to the yearly national fossil fuel emissions for the 10 biggest emitters in order to put these figures into context (Fig. 1d). The five-month emissions for 2023 are more than four times higher than the annual emissions from fossil fuels in Canada.

A number of intricate factors, such as fuel characteristics20 and ignition probability21, influence fire activity. Nonetheless, it has been demonstrated that hot, dry weather has a significant role in determining fire behavior22. Climate statistics indicate that the fire season in Canadian forests in 2023 will be unusually hot and dry (Fig. 2).

Fires and Climate:

Figure 3 explores the relationship between climate variability and fire emissions fo Canadian forests by plotting fire emissions as a function of temperature and precipitation Z-scores for the 0.5° × 0.625° grid cells from 2003 to 2023. Z-scores are calculated by dividing anomalies by the standard deviation. When combination cool-wet conditions are present, emissions are lowest from May to September (5.2 gC m^{-2}). Conversely, when temperature is above average (19.5 gC m^{-2}) or precipitation is below average (9.2 gC m^{-2}), emissions rise. On the other hand, combined warm-dry circumstances result in the highest emissions (35.7 gC/m^{-2}). Specifically, when conditions are particularly hot and dry (temperature Z > 1, precipitation Z < 1, and 99.6 gC m^{-2}), fire emissions are significantly increased.

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In 2023, these hot, dry conditions were far more common than they were in previous years, with a mean T2M Z-score of 2.3 for May–September and a Z-score of -1.1 for precipitation across grid cells, which explains why fire Extreme sions occurred in 2023. Notably, the quantity of distinct fires was not out of the ordinary for 2023, with 6,623 compared to a 10-year average.

With over 86% of the wooded region experiencing below-normal precipitation and approximately 52% falling more than one standard deviation below the 2003–2022 average, this January–September period was the driest for Canadian forests since at least 1980 (Supplementary Fig. 4). With over 90% of the forest area being greater than one standard deviation above the 2003–2022 average and nearly 100% of the forest area being above average, May–September 2023 was the warmest since at least 1980. Likewise, the vapour pressure deficit (VPD), which is directly linked to fire activity22–24, reached its third-highest level since 1980, with 85% of the forest area exceeding average and roughly 54% exceeding one standard deviation above the 2003–2022 average.

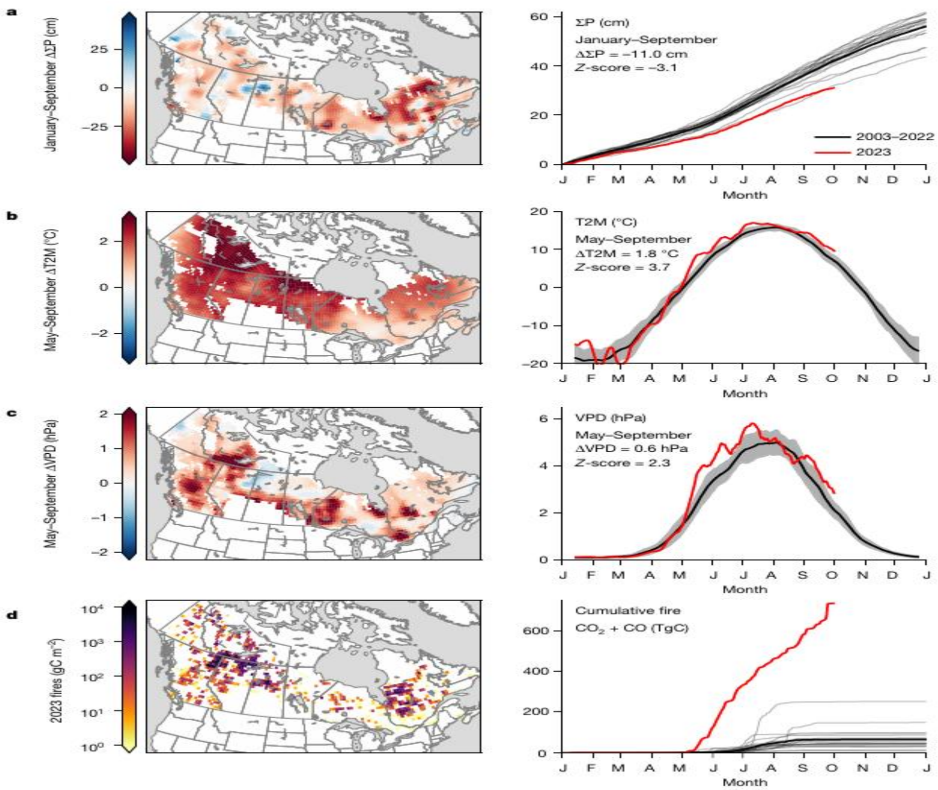

Figure 2: Climate anomalies for Canadian woods in 2023 compared to the mean for 2003–2022. a–d, Maps (left) and time series (right) of fire CO_2 + CO emissions from the GFED4.1s database (d), MERRA-2 2 m temperature (with a 2-week running mean) (b), MERRA-2 VPD (with a 2-week running mean) (c), and CPC global uniform gauge-based cumulative precipitation (∑P) (a). The geographic resolution of all maps is 0.5°×0.625°, and the area-mean of Canadian woods is used to calculate Z-scores. The inversion results are displayed at a finer spatial resolution and span a shorter time period, therefore GFED4.1s is displayed instead. Maps of the previous and posterior mean fire emissions are displayed in Supplementary Fig. 14. The months from January (J) to December (D) are displayed.

5,597 (source 25). However, many of these fires developed to gigantic magnitude, with hundreds of megafires (greater than 10,000 ha) documented. This was likely mostly caused by the hot, dry conditions24.

We next look at the climate circumstances that the area would experience in the future and compare them to the ones that existed at the same time and caused the big flames. Under the moderate-warming shared socioeconomic pathway (SSP)2-4.5, Figure 3 displays the decadal mean temperature and precipitation Z-scores for the median of 27 models from the coupled model intercomparison project phase 6 (CMIP6)26 (ref. 4).

The average temperature in the 2050s is determined to be similar to that of 2023, with significant predicted temperature rises occurring. Precipitation is expected to increase more moderately, suggesting a "speeding up" of the water

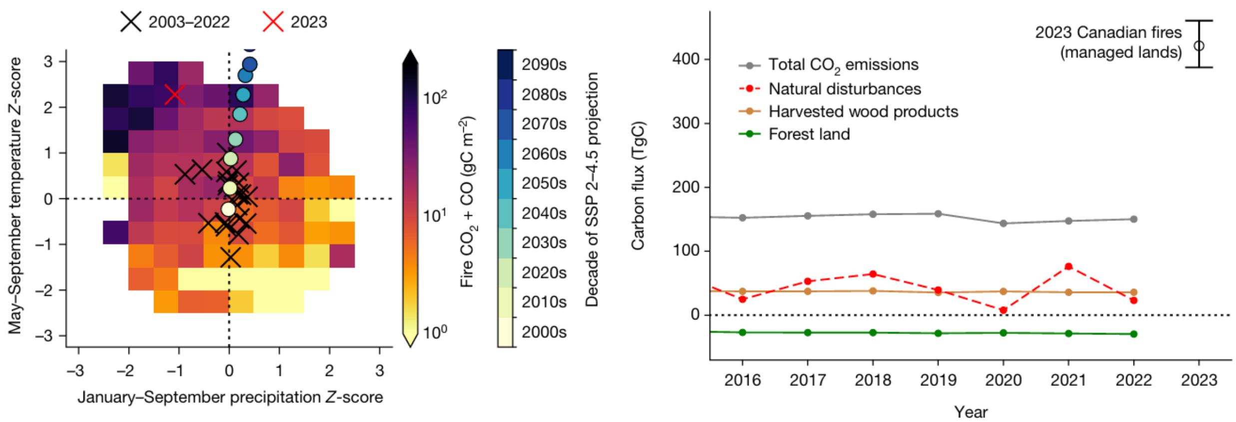

Figure 3: Fire emissions and climate anomalies in relation to each other.

Average May–September CO2 GFED4.1s+ CO emissions in relation to May T2M Z-score for September and the precipitation Z-score for January–September for every grid cell with 0.5°×0.625° of forest cover between 2003 and 2023 (considering 2003–2022 as a baseline). In specific years, the average Z-scores among grid cells with forests are displayed with 'X'. The anticipated precipitation and temperature on a decadal scale The circles display Z-scores for the median CMIP6 model under SSP 2-4. The baseline period used to generate the CMIP6 Z-scores is 2000–2019. but utilize the reanalysis standard deviations for 2003–2022 (see the "Climate" section data). Precipitation across the Canadian Arctic and historical and forecast T2M Supplementary displays the CMIP6 ensemble's simulation of boreal forests. Figure 12.

Through the end of the twenty-first century, the combined effect will cause regional increases in moisture deficits for Canadian forests6,27,28. It is predicted that average temperatures and precipitation levels will rise above historical ranges after the year 2050.

The boreal carbon cycle will be impacted by these changes in a variety of ways, including altered fuel loads and species composition, which makes predictions about future fire activity more difficult. But recent reports have indicated increases in emissions from boreal fires associated with global warming13,27,29,30, and other studies have predicted that future warming will lead to much greater increases in fire activity in Canada5-8. Therefore, we discover that rising temperatures along with locally growing moisture deficiencies are probably going to cause a rise in fire carbon emissions from Canadian woods.

Figure 4 compares Canada's NGHGI CO2 emissions and removals with the Canadian fires of 2023. The lines represent the annual net emissions or removals from harvested wood products (brown), natural disturbances that are not included in Canada's emissions (red), and the net CO2 emissions for the entire economy (grey). Black represents the top-down projections of the CO2 + CO fire emissions over controlled land in 2023. Total carbon dioxide

Table A11-1 of the NGHGI32 provided the emissions, harvested wood products, and forest land emissions and removals; Table 6-5 of the NGHGI provided the information on natural disturbances. The amounts displayed are all expressed in teragrams of carbon (1 TgC = 1 MtC = 1,012 gC), which can be multiplied by to get megatonnes of CO2 (MtCO2) units.

Canadian carbon budget implications:

Canada is required to measure economy-wide greenhouse gas (GHG) emissions and removals in a national GHG database as a party to the Paris Agreement. inventory (NGHGI). This involves monitoring the emissions and extractions from"managed" areas, wherein actions and interventions by humans have been used to carry out social, ecological, or production tasks31. Still, the Intergovernmental Panel on Climate Change (IPCC) report from 2006 criteria for Canadian NGHGI32 and national GHG inventories31 are different. in the classification of emissions and removals from managed lands. All emissions and removals from managed land are included by the IPCC recommendations. while the Canadian NGHGI views "natural disturbances" as man-made. Banches as a non-human being. This classification discrepancy results in significant variations between the Canadian NGHGI and an approximation made using the definitions of IPCC guidelines.

Figure 4 illustrates how emissions from harvested wood products nearly completely offset NGHGI reductions on managed forest land. As a result, the energy sector accounts for more than 90% of Canada's total net emissions of CO2. On the other hand, it is evident that natural disruptions are of a significant size, accounting for around 60% of all CO2 emissions in 2021. The CO_2 + + emissions from fires in Canada's managed forests in 2023 (see section

on "Managed land") are projected to be 421 (388–461) TgC, or 2.5–3 years' worth of CO_2 emissions for the entire economy.

The pace at which atmospheric CO_2 grows will be impacted by fire carbon emissions, regardless of how they are classified. It is crucial to keep an eye on changes in the carbon budget for both managed and uncontrolled land. Top-down estimates, which incorporate all land in the Canadian carbon budget, show that, whether limited by in situ or space-based CO_2 data, Canadian ecosystems function as a sink of CO_2. An ensemble of atmospheric CO_2 inversion systems, using both types of data, find that throughout the period of 2015–2011, Canadian carbon stocks rose by 366 ± 88.6 TgC yr^{-1}, accounting for approximately 30% of the net land carbon sink. Similar to this, but smaller, space-based biomass estimations reveal carbon buildup in Canadian boreal forests.

As a result, Canadian woods are crucial in reducing anthropogenic emissions and delaying the increase in atmospheric CO_2. The longevity of this sink is called into question by the significant carbon release that comes from the Canadian wildfire in 2023. Others13 demonstrated how, during the previous 30 years, fires have suppressed the capacity of Canadian forests to absorb carbon. Large stand-replacing fires have traditionally occurred in Canadian forests at irregular periods of 30 to more than 100 years35–37; however, an increase in fire frequency is likely to decrease biomass recovery and have an impact on species composition 37–40. Additionally, it has been suggested that Canadian woods may already be turning into a carbon source due to fire, insects, and droughts41, 42. In the unlikely event that large-scale flames like the one in 2023 (which burned 4% of the land) become commonplace

It's also important to talk about how Canada's fire management policy controls carbon emissions from fires. When developing fire control techniques, it's important to balance a number of factors, such as carbon emissions, ecological effects, and socioeconomic costs. The current system used by Canada is risk-based, meaning that provinces and territories have different priorities when it comes to 4 | Nature | fire suppression, and decisions are decided on a fire-by-fire basis43. It is therefore crucial to comprehend how 17. fire regimes will alter as a result of climate change in order to inform future decision-making processes and budgets.

Data availability

The dataset produced for this study can be accessed at JPL Open Reposi tory, https://doi.org/10.48577/jpl.V5GR9F. Code availability The Python and Bash codes used in this study are available at Zenodo (https://doi.org/10.5281/zenodo.12709398)75

Online Content:

Any methods, additional references, Nature Portfolio reporting summa ries, source data, extended data, supplementary information, acknowl edgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-024-07878-z.

Climate Data:

The National Oceanic and Atmospheric Administration's daily precipitation data, which can be accessed at https://psl.noaa.gov, was the source of the precipitation estimates, which were obtained by the Climate Prediction Center's (CPC) global unified gauge-based analysis (refs. 44, 45). From the single-level diagnostics file3, the MERRA-2 2 m temperature (T2M) and the dew point temperature at 2 m (T2MDEW) were acquired. From these values, the VPD was computed using:

VPD=es−ea

where es is the saturation vapour pressure and ea is the vapor pressure, which are determined using the formulation of reference 46 from T2MDEW and T2M, respectively. The Z-scores for precipitation, T2M, and VPD were computed in relation to the 2003–2022 20-year baseline. For T2M, this can be done as follows:

Conclusions:

There were significant carbon emissions from forest fires in 2023 since it was the warmest and driest fire season for Canadian woods since at least 1980.

We calculate the cumulative May–September CO2 + CO emissions from these fires to be 647 TgC (range 570–727 TgC) based on TROPOMI CO retrievals. This amount is similar to India's yearly CO2 emissions from fossil fuels.

Based on the previous 44 years, the warmth of 2023 was unusual, but CMIP6 climate models predict that by the 2050s, the 2023 temperatures will return to normal. These alterations are probably going to lead to a rise in fire activity, which puts Canadian forests' capacity to absorb carbon at risk. This will affect the permitted emissions to meet warming targets since ecosystems' decreased capacity to sequester carbon dioxide needs to be made up for by modifying the reduction of manmade emissions.