

Drought and overwintering fires drive consecutive large fire seasons in boreal North America

Rebecca Scholten

`rebecca.scholten@uci.edu`

University of California, Irvine <https://orcid.org/0000-0002-0144-0572>

Yang Chen

University of California, Irvine <https://orcid.org/0000-0002-0993-7081>

Robert Field

Columbia <https://orcid.org/0000-0003-3001-5580>

Jinhyuk Kim

University of Michigan

William Burrows

Environment and Climate Change Canada

Richard Carr

Northern Forestry Centre <https://orcid.org/0000-0002-9291-8980>

Tianjia Liu

University of British Columbia

Tempest McCabe

NASA Goddard Space Flight Center

Douglas Morton

National Aeronautics and Space Administration <https://orcid.org/0000-0003-2226-1124>

Angela Rigden

University of California, Irvine <https://orcid.org/0000-0003-3876-6602>

Brendan Rogers

Woodwell Climate Research Center <https://orcid.org/0000-0001-6711-8466>

James Randerson

University of California, Irvine <https://orcid.org/0000-0001-6559-7387>

Physical Sciences - Article

Keywords:

Posted Date: July 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9918381/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

Drought and overwintering fires drive consecutive large fire seasons in boreal North America

Rebecca C. Scholten^{1,*}, Yang Chen¹, Robert Field^{2,3}, Jinhyuk E. Kim⁴, William Burrows⁵,
Richard Carr⁶, Tianjia Liu⁷, Tempest McCabe^{8,9}, Douglas C. Morton^{8,9}, Angela J. Rigden¹,
Brendan M. Rogers¹⁰, James T. Randerson^{1,11}

¹ Department of Earth System Science, University of California, Irvine

² Department of Applied Physics and Applied Mathematics, Columbia University, New York

³ NASA Goddard Institute for Space Studies, New York

⁴ Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor

⁵ Environment and Climate Change Canada, Edmonton, Canada

⁶ Northern Forestry Centre, Edmonton, Canada

⁷ Department of Geography, University of British Columbia, Vancouver, Canada

⁸ NASA Goddard Space Flight Center, Greenbelt, Maryland

⁹ University of Maryland, College Park

¹⁰ Woodwell Climate Research Center, Falmouth, MA

¹¹ Department of Civil and Environmental Engineering, University of California, Irvine

*Corresponding author. Email: rebecca.scholten@uci.edu

Boreal North America experienced unprecedented consecutive extreme fire seasons during 2023–2025, marked by record-breaking burned area and emissions. We identify a series of interconnected mechanisms that enabled these back-to-back extremes. A multi-year drought—the most severe in at least 45 years—lowered the water table and desiccated

organic soils, allowing more fires to persist over winter under the snowpack. In 2024 and 2025, 14–22% of the burned area in boreal North America originated from overwintering fires. Spring terrestrial water storage anomalies predicted subsequent fire activity, indicating that hydrological monitoring can provide early warning months in advance. These multi-year carryover effects challenge current fire danger systems that treat seasons independently and demonstrate that multi-year climate variability can override long-term wetting trends predicted under climate change.

Arctic-boreal regions are experiencing accelerated climate warming at rates 2–4 times the global average¹, leading to observed increases in burned area^{2,3} and fire intensity^{4,5}. Rather than gradual shifts, these changes are driven by an increase in extreme events, resulting in unprecedented fire sizes³, annual burned area^{6,7}, and fire emissions^{8,9} in recent years. More remarkably, such extremes in recent years have been occurring consecutively, for example, in Eastern Siberia during 2019–2021¹⁰, and in Canada during 2023–2025¹¹. In 2023 alone, an estimated 4% of Canada's forests burned¹², producing a record of 647 Tg of carbon emissions⁸. This record-breaking event was followed by two additional severe years in 2024 and 2025⁶. Consecutiveness at such extreme magnitudes is unexpected given that fire return intervals in high latitude regions are generally between 80 and several hundred years^{13–15}, and fires are thought to be at least partly self-limited as fuel availability declines following large burns in these slow-growing forest and tundra ecosystems^{16,17}.

The mechanisms enabling successive extreme fire years remain poorly understood. Individual extreme fire years typically develop when a relatively brief window of convergent fire weather conditions, including high temperatures, low precipitation, and strong winds¹⁸ is facilitated by atmospheric blocking^{10,19} and exceptional lightning activity^{20,21}. Consecutive extremes, in contrast, require some combination of 1) a persistent multi-year climate driver that

maintains anomalous conditions across seasons, 2) carryover effects that link successive fire seasons across years, or 3) the presence of a positive feedback loop that operates across seasons. Low-frequency climate oscillations such as El Niño-Southern Oscillation or the Pacific Decadal Oscillation (PDO) influence fire activity in tropical²² and, to a lesser degree, in subtropical regions²³; however, they remain weak predictors of fire extremes in the boreal domain²⁴. At decadal time scales, the PDO has been associated with increased drought and fire activity in western boreal North America during positive phases^{25,26}, but has been negative since 2018 and thus cannot account for the recent uptick in extreme fire years. Fuel dryness associated with drought is an important driver of burned area across western and boreal North America^{27–30}, but drought persistence beyond annual time scales is poorly understood. Studies using, for example, Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage anomalies show increasing^{31–33}, decreasing³⁴, and spatially varying trends^{35–37} in the region.

Carryover effects may link successive fire seasons through mechanisms such as legacy fuel conditions (for example, buildup of litter or deadwood) or fires that survive the winter to reignite in subsequent years. These overwintering "zombie" fires smolder through winter in organic soils or tree roots³⁸ and can reignite when conditions become favorable in spring³⁹. Overwintering fires have been documented as minor contributors (<1%) to annual burned area in boreal regions during 2001–2018³⁹. Slightly elevated contributions (7.5%) were observed during Siberia's 2019–2021 consecutive fire extremes⁴⁰. News reports of smoke from overwintering fires throughout the winter of 2023–2024 in western Canada⁴¹ suggest their contribution during the 2023–2025 Canadian extremes may be larger than expected, particularly under extreme drought conditions.

Positive feedbacks can intensify drought conditions and amplify their influence on wildfire dynamics through land-atmosphere interactions or changes in fuel conditions. Depleted soil moisture during drought reduces evapotranspiration and increases sensible heat fluxes, which can

intensify heatwaves and accelerate the drying of dead surface fuels^{42–44}. Dry soils can also influence precipitation patterns⁴⁵ by decreasing moisture recycling⁴⁶ and promoting persistent anticyclonic circulation⁴⁷, which induces persistent dry weather and suppresses clouds and precipitation, prolonging dry conditions during the fire season. Earlier snowmelt, induced by reduced snowpack and spring warming, can also advance the timing of vegetation green-up, further accelerating evaporation-driven feedbacks⁴⁸. These processes can dry fuels earlier in the growing season, leading to an earlier onset of the fire season^{49–51} and enabling fires to grow larger⁵². Fire-emitted aerosols may further reinforce drought conditions by increasing cloud condensation nuclei concentrations, suppressing precipitation and enhancing atmospheric stability in boreal regions^{53,54}.

The relative importance of multi-year climate anomalies, carryover effects, and self-reinforcing feedbacks in enabling back-to-back extremes in boreal ecosystems remains unresolved. In recent years, boreal North America has emerged as a hotspot area of fire extremes, offering a testbed for assessing these contributions. Here, we investigate the drivers of consecutive large fire seasons in this region during 2023–2025. We first demonstrate that the hydrological drought in western interior and central Canada during this period was the largest in the last 45 years. We hypothesize that two drought-related mechanisms created carryover effects linking these extreme fire years: 1) a substantially larger contribution from overwintering fires than previously assumed, and 2) land-atmosphere feedbacks that amplified vegetation green-up in spring, leading to an earlier fire season onset and accelerated summer fuel curing. We focus our analysis on three hotspot regions in western, central, and eastern Canada that exhibited distinct burning patterns across the three years. To disentangle these interconnected drivers, we trace the evolution of the multi-year drought using GRACE terrestrial water storage anomalies and reconstruct its underlying causes by analyzing precipitation and evapotranspiration anomalies. We then examine

how drought-driven changes in spring vegetation dynamics altered fuel availability and fire season timing, linking hydrological deficits to land-atmosphere feedbacks that primed the landscape for extreme burning. Finally, we quantify the spatial extent and contribution of overwintering fires by tracking individual fire perimeters across years and assessing their relationship to antecedent drought conditions.

A severe multi-year drought drives fire extremes in western Canada

The 2023–2025 fire seasons were exceptional not only in their individual magnitudes but also in their occurrence as consecutive extreme years, and their total sum of burned area and emissions. Over the three years, the cumulative burned area recorded by the Arctic-boreal Fire Atlas⁵⁵ was 35.5 Mha in boreal North America. Burning was concentrated in three main hotspot regions in western, central, and eastern Canada (Fig. 1A). Carbon emissions from the Global Fire Emission Database version 5 (GFED5) near-real time extension⁵⁶ were 0.6 Pg C in the western region (Fig. 1B), 0.3 Pg C in the central region (Fig. 1C), 0.1 Pg C in the eastern region (Fig. 1D), and 1.2 Pg C for the full domain (Fig. 1E). The western and central regions experienced sustained fire activity across all three years, while the eastern region (primarily Québec) burned extensively only in 2023 (fig. S1).

Persistent deficits in terrestrial water storage (TWS), measured by GRACE, preceded and accompanied the consecutive extreme fire seasons of 2023–2025, suggesting an important hydrological preconditioning of these events (Fig. 2). Across western and central Canada, TWS declined rapidly during the second half of 2022, well before the onset of the record fire activity. In western Canada, TWS anomalies at the end of the fire season in October ranged between –220 and –255 mm during 2023–2025 (Fig. 2A), about 4.0 standard deviations below the climatological mean (-73 ± 41 mm) derived from 2002–2021 observations (table S1). Central Canada exhibited

a similar pattern (Fig. 2B), with persistent negative anomalies throughout 2023–2025 near the end of each fire season that were considerably lower than the climatological mean (table S1). In eastern Canada, TWS dropped sharply in early 2023, coinciding with Québec’s extreme fire season and reaching a minimum of -106 mm in October, before gradually recovering during 2024–2025 (Fig. 2C).

To assess whether the western Canadian drought was exceptional in the historical record, we reconstructed TWS anomalies for each region for a pre-GRACE period from 1980 to 2002 using a water balance model with independent precipitation (P) and evapotranspiration (E) data, along with a drainage term (model $R^2 = 0.71\text{--}0.85$, RMSE = $23\text{--}32$ mm, table S2). Precipitation data stemmed from the Global Precipitation Climatology Project and evapotranspiration from the Global Land Evaporation Amsterdam Model. The reconstruction revealed that the 2023–2025 drought was the most severe in the 45-year record in the western ($z = -4.0 - -5.8$) and central regions ($z = -3.4 - -5.5$, fig. S2, table S1). By replacing either observed P or E with the climatological average, we then quantified the relative contribution of each component to the TWS anomalies (Methods, table S3). Decomposition of the TWS anomalies shows that precipitation deficits accounted for 75–77% of the water storage deficit in western Canada and 82–85% in central Canada when evapotranspiration was held at climatological values, while elevated evapotranspiration contributed to 23–25% in the western region and 15–18% in the central region, when precipitation was held at climatological values (fig. S3, table S3), confirming that precipitation deficits were the dominant driver.

Coinciding with the drought onset, precipitation and top layer soil water deficits in western Canada emerged in summer of 2022 and persisted throughout 2025, with particularly strong deficits during summer and autumn (fig. S4B,E). In contrast, annual evapotranspiration anomalies were relatively small, though spring evapotranspiration was consistently elevated in 2023–2025

(fig. S4C). The resulting water balance ($P - E$) and top layer soil water showed deficits recurring in summer of all three years, with an exceptionally strong deficit in spring 2023 (fig. S4D,E). While conditions in central Canada mirrored those in the West, they differed markedly in eastern Canada, where the co-occurrence of low precipitation and high evapotranspiration in spring 2023 lead to a strong seasonal water balance and TWS deficit, followed by near-normal $P-E$ conditions in 2024–2025 consistent with minimal fire activity in those years.

Modeled terrestrial water storage (TWS) anomalies in May, reflecting the initial hydrological state at the onset of the fire season, were a strong pre-season predictor of annual burned area during 1980–2025 (Pearson $r = -0.50$, $p < 0.001$, Fig. 3A). While summer (JJA) VPD was the strongest regulator for burned area overall with an adjusted R^2 of 0.43 for a regression model with an exponential function (Fig. 3B), adding May TWS into the model improved model fit, increasing the R^2 to 0.51 (table S4), indicating that water storage deficits at the start of the fire season are an important additional driver of fire extremes. TWS especially improved model fit in the western region, increasing the adjusted R^2 from 0.55 for the VPD-only model to 0.69 for the full model (fig. S5). While May showed the strongest predictive power, predictability was high even as early as January, especially in the West ($r = -0.39$, $p < 0.001$, table S5).

Drought facilitates large overwintering fires in western peatlands

We hypothesize that extreme terrestrial water storage deficits increase the likelihood of fires persisting throughout the winter, especially in deep organic soils (fig. S6). To test this, we tracked individual fires across each year, identifying "overwintering ignitions" as fires that started within 1 km of a previous year's burn edge and did not occur in vicinity of a recorded lightning strike (Fig. 4, fig. S7). Analysis of the western hotspot region revealed that 145 fires (1.1 Mha) in 2024 and 138 fires (0.5 Mha) in 2025 originated from previous burn perimeters (Fig. 4A, table

S6). May TWS was strongly negatively correlated with the number of overwintering fire ignitions in 2012–2025 ($r = -0.74$, $p < 0.001$, fig. S8C), indicating that a lower water table enabled fires to persist through winter in deep organic soils and re-emerge the following spring. Overwintering ignitions in 2024–2025 accounted for 19–27% of burned area and 18–24% of carbon emissions in the western region, and 1–8% of burned area and 1–9% of carbon emissions in the central region (Fig. 4C–F, table S6). Notably, we observed fires in 2025 reigniting from 2023 burn perimeters in both western and central regions, indicating that overwintering could persist for two years after the initial burn (Fig. 4).

Overwintering fires also occurred disproportionately in peatland-rich areas (shaded area in Fig. 1A), indicating that water table decreases associated with the drought may increase the likelihood of peat smoldering throughout winter. In 2024–2025, 44% of overwintering fire starts occurred in mapped peatlands⁵⁷, compared to 32% for non-overwintering fires ($\chi^2 = 27.1$, $p < 0.001$). More broadly, fires in 2023–2025 burned a substantially higher fraction of peatland area than the long-term (1980–2022) mean across western and central Canada (west: 33.5% vs. 16.3%, $z = 1.6$, $p = 0.003$; central: 28.2% vs. 17.0%, $z = 1.2$, $p = 0.02$), and all the regions saw record-breaking levels of peatland burning in at least one year (west: 2023–2024, central: 2025 and east: 2023, fig. S9). These patterns suggest that drought enabled burning in typically fire-resistant, carbon-rich landscapes and likely promoted higher-severity burning that amplified regional fire carbon emissions.

Overwintering fires can induce an early start of the fire season and significantly enhance early-season burning. While the number of other fire starts was highest during the summer lightning season in July, the start date of overwintering fires peaked in May (fig. S10A). These fires thus contributed disproportionately to early-season burning: in 2024, overwintering fires accounted for 66% of total burned area in May and 42% in June, far exceeding their 22%

contribution to annual burned area (fig. S10B). Numerous overwintering fire starts were detected as early as January, weeks to months before starting to spread in mid- to late May, potentially presenting opportunities for early intervention.

Spring and summer hydrological drought and biosphere-atmosphere feedbacks

The severe hydrological drought in western Canada increased annual burned area through several reinforcing processes operating across the fire season (figs. S6, S8). A striking feature of 2023–2025 was an anomalously early fire season onset (fig. S1D–F), with 2023 and 2025 showing particularly high levels of burning in May and June—a period when widespread fire activity is typically limited (fig. S1A–C). Low water storage in May was strongly associated with earlier fire-season start dates ($r = 0.70$, $p < 0.001$, fig. S8A), as spring TWS deficits likely accelerated fine fuel drying following early snowmelt.

Gross primary productivity data revealed an early green-up, likely triggered by an earlier snowmelt and spring warming (fig. S4G), which may have initiated land-atmosphere feedbacks that amplified drought and fire activity later in the season⁴³. Elevated evapotranspiration from earlier vegetation activity intensified soil moisture depletion (fig. S4C,E), reducing evaporative cooling and potentially contributing to surface warming and the observed summer VPD extremes (fig. S4F). While spring drought, represented through May TWS anomalies was correlated with summer VPD ($r = -0.41$, $p < 0.001$), a definitive attribution of these feedbacks would require controlled modeling experiments that isolate land-atmosphere coupling. Throughout the active fire season, spring TWS deficits showed weak associations with the number of fire ignitions ($r = -0.24$, $p = 0.12$, fig. S8B). Finally, high summer VPD and low precipitation were associated with a later end of the fire season (VPD: $r = 0.72$, $p < 0.001$; Precipitation: $r = -0.71$, $p < 0.001$, figs. S8D, S1D–F).

Early warning and management of drought-driven fire extremes

CMIP6 models project that Arctic-boreal regions will become both warmer and wetter under climate change^{58–61}, observed through increases in Arctic river discharges^{62,63}. These climate-driven changes in the northern hydrological cycle are consistent with observed increases in precipitation in recent decades^{64–66}. Such precipitation increases should, in theory, partly offset fire risk from rising temperatures, but there is not strong agreement across CMIP6 aridity metrics in the strength of this offsetting⁶⁷. Our results reveal that the 2023–2025 Canadian fire extremes occurred during the most severe drought in the 45-year observational record (1980–2025), driven overwhelmingly by sustained precipitation deficits (accounting for 80–89% of water storage decline) and to a lesser degree by increased evapotranspiration. This demonstrates that decade-scale climate variability can produce severe hydrological droughts that create conditions for unprecedented fire activity, even within a wetter long-term trajectory. The mechanisms we identify, including multi-year water storage depletion, overwintering fires, and land-atmosphere feedbacks, depend primarily on hydrological deficits rather than temperature extremes alone, suggesting that drought monitoring may be a critical addition for seasonal fire risk predictions. On longer time scales multi-year droughts have the potential to amplify wildfire risk that is expected from increasing VPD and fire weather during summer^{3–5,18}.

Current operational fire danger systems often do not account for multi-year drought effects that link successive fire seasons. The Canadian Fire Weather Index (FWI) system forms the basis for fire danger forecasts across much of the boreal zone because of its simplicity and ability to track the slow and fast aspects of the fire environment. It is, however, limited in propagating multi-year drought memory: the standard overwintering procedure⁶⁸ adjusts spring drought code (DC) startup based solely on the preceding fall moisture deficit and fixed recharge coefficients^{69–71}. Our findings demonstrate that carryover effects and, potentially, self-reinforcing feedbacks triggered

by a multi-year drought are substantial drivers of consecutive fire extremes, underscoring the need to incorporate multi-year hydrological state variables, including water table conditions, into fire danger systems. Relatively simple hydrological metrics from GRACE satellite observations or regionally calibrated water balance models may serve as important additional early warning indicators for extreme fire seasons months in advance and in springtime startup of the FWI. While TWS in May was the strongest pre-fire season predictor of burned area, significant correlations were observable as early as January. FWI startup procedures could thus be modified to reflect springtime TWS or organic soil moisture anomalies, adjusting initial DC values directly based on water storage conditions.

Contrary to previous research³⁹, we show that overwintering fires can contribute substantially to large fire years, especially early in the fire season. The extended smoldering times of overwintering fires observed between the first detection and large spread present an opportunity for fire management intervention that current systems do not exploit. Their systematic monitoring and forecasting should therefore be integrated into operational systems. Real-time monitoring of burn perimeters from the previous season, combined with modeled or observed TWS or soil moisture forecasts at skillful lead times, could identify high-risk areas for overwintering fire activity months before peak fire season, enabling cost-efficient suppression of smoldering overwintering fires when fire management resources are not yet strained³⁹. The disproportionate occurrence of overwintering fires in carbon-rich peatlands indicates that such targeted attack of these fires could also yield important carbon gains, presenting a low-cost natural climate solution^{72,73}.

Disproportional impacts of consecutive fire extremes

Consecutive fire extremes create disproportional impacts compared to their cumulative burned area, as ecosystems and communities lack time to recover between events. Ecologically, back-to-back large fire years increase the probability of short-interval reburning, releasing legacy carbon⁷⁴ and fueling ecosystem transitions¹⁵. Large-scale burning at the landscape level may impede regeneration when increased distances to seed sources exceed dispersal capabilities⁷⁵. Large regional burned area also induces albedo feedbacks during summer that can lead to surface warming, compounding the drought stress on seedling establishment⁷⁶. We also show that fires in 2023–2025 burned a disproportionately high fraction of peatland, rendering these normally fire-resistant, carbon-rich landscapes vulnerable. More broadly, higher fire severity⁷⁷ under prolonged drought may have increased carbon emissions and tree mortality, and may at longer time scales transform fire regimes and ecosystems³⁰.

The societal impacts of consecutive fire extremes remain understudied but are potentially severe. The 2023 wildfires in Canada alone had outsized impacts on local populations through evacuations, smoke pollution, and economic damages⁷⁸. Repeated exposure to smoke over multiple fire seasons compounds health impacts, in particular for Indigenous populations in northern regions who face prolonged poor air quality with limited access to mitigation resources^{6,79}. Consecutive extreme fire years erode community resilience through repeated evacuations, property losses, reduced revenue from tourism, and destruction of resources for subsistence that provide food security and cultural continuity⁸⁰. The 2023–2025 period saw multiple communities evacuated across western Canada in successive years, creating cumulative trauma and economic hardship that may accelerate permanent displacement or out-migration from rural and Indigenous communities. Transboundary smoke impacts affected millions of people in North America in 2023^{67,81,82}, and to a lesser extent in 2024–2025, demonstrating that consecutive fire extremes generate cascading public health and economic costs that extend across borders and

accumulate over years. Understanding and mitigating these compounding societal impacts should be a priority for adaptation planning as consecutive fire extremes may become more frequent in a rapidly changing climate.

References and Notes

1. Rantanen, M. *et al.* The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment* **3**, 168 (2022).
2. Jones, M. W. *et al.* Global and regional trends and drivers of fire under climate change. *Reviews of Geophysics* 1–76 (2022) doi:10.1029/2020rg000726.
3. Hanes, C. C. *et al.* Fire regime changes in Canada: an update. *Can. J. For. Res.* **55**, 1–11 (2025).
4. Li, Y., Janssen, T. A. J., Chen, R., He, B. & Veraverbeke, S. Trends and drivers of Arctic-boreal fire intensity between 2003 and 2022. *Science of The Total Environment* **926**, 172020 (2024).
5. Cunningham, C. X., Williamson, G. J. & Bowman, D. M. J. S. Increasing frequency and intensity of the most extreme wildfires on Earth. *Nat Ecol Evol* **8**, 1420–1425 (2024).
6. Tymstra, C. & Flannigan, M. Canada’s landscape fires spreading into uncharted territory. *Environ. Res. Lett.* **20**, 111003 (2025).
7. Descals, A. *et al.* Unprecedented fire activity above the Arctic Circle linked to rising temperatures. *Science* **378**, 532–537 (2022).
8. Byrne, B. *et al.* Carbon emissions from the 2023 Canadian wildfires. *Nature* **633**, 835–839 (2024).

9. Zheng, B. *et al.* Record-high CO₂ emissions from boreal fires in 2021. *Science (New York, N.Y.)* **379**, 912–917 (2023).
10. Scholten, R. C., Coumou, D., Luo, F. & Veraverbeke, S. Early snowmelt and polar jet dynamics co-influence recent extreme Siberian fire seasons. *Science* **378**, 1005–1009 (2022).
11. Chen, Y., Field, R. D., Scholten, R. C. & Randerson, J. T. Persistent 2023–2025 Wildfire extremes in Canada produced unprecedented emissions and air-quality impacts. *Global Change Biology* (in press).
12. Jain, P. *et al.* Drivers and impacts of the record-breaking 2023 wildfire season in Canada. *Nat Commun* **15**, 6764 (2024).
13. Kharuk, V. I., Dvinskaya, M. L., Petrov, I. A., Im, S. T. & Ranson, K. J. Larch forests of Middle Siberia: long-term trends in fire return intervals. *Regional Environmental Change* **16**, 2389–2397 (2016).
14. Burrell, A. L. *et al.* Climate change, fire return intervals and the growing risk of permanent forest loss in boreal Eurasia. *Science of The Total Environment* **831**, 154885 (2022).
15. Baltzer, J. L. *et al.* Increasing fire and the decline of fire adapted black spruce in the boreal forest. *Proceedings of the National Academy of Sciences* **118**, e2024872118 (2021).
16. Janssen, T. A. J. & Veraverbeke, S. What are the limits to the growth of boreal fires? *Global Change Biology* **31**, e70130 (2025).
17. Parks, S. A., Holsinger, L. M., Miller, C. & Nelson, C. R. Wildland fire as a self-regulating mechanism: The role of previous burns and weather in limiting fire progression. *Ecological Applications* **25**, 1478–1492 (2015).
18. Wang, X. *et al.* Increasing frequency of extreme fire weather in Canada with climate change. *Climatic Change* **130**, 573–586 (2015).

19. Jain, P. & Flannigan, M. D. The relationship between the polar jet stream and extreme wildfire events in North America. *Journal of Climate* 1–59 (2021) doi:10.1175/jcli-d-20-0863.1.
20. Veraverbeke, S. *et al.* Lightning as a major driver of recent large fire years in North American boreal forests. *Nature Climate Change* **7**, 529–534 (2017).
21. Burrows, W. R., Kochtubajda, B. & Fricska, G. Cloud-to-ground lightning trends in Canada and regions of the United States North of 40°N 1999–2023. *Atmosphere-Ocean* **63**, 125–146 (2025).
22. Chen, Y. *et al.* A pan-tropical cascade of fire driven by El Niño/Southern Oscillation. *Nature Climate Change* **7**, 906–911 (2017).
23. Macias Fauria, M. & Johnson, E. A. Climate and wildfires in the North American boreal forest. *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**, 2317–2329 (2008).
24. Zhao, Z., Lin, Z. & Li, F. Influence of atmospheric teleconnections on interannual variability of boreal fires. 95 (2020).
25. Macias Fauria, M. & Johnson, E. A. Climate and wildfires in the North American boreal forest. *Phil. Trans. R. Soc. B* **363**, 2315–2327 (2008).
26. Ryzhkova, N. *et al.* PDO Dynamics shape the fire regime of boreal subarctic landscapes in the Northwest Territories, Canada. *JGR Biogeosciences* **130**, e2024JG008178 (2025).
27. Wang, W. *et al.* The extent of drought determines daily area burned in Canadian forests. *Environ. Res. Lett.* **20**, 124076 (2025).
28. Xiao, J. & Zhuang, Q. Drought effects on large fire activity in Canadian and Alaskan forests. *Environ. Res. Lett.* **2**, 044003 (2007).

29. Meyn, A., Taylor, S. W., Flannigan, M. D., Thonicke, K. & Cramer, W. Relationship between fire, climate oscillations, and drought in British Columbia, Canada, 1920–2000. *Global Change Biology* **16**, 977–989 (2010).
30. Littell, J. S., Peterson, D. L., Riley, K. L., Liu, Y. & Luce, C. H. A review of the relationships between drought and forest fire in the United States. *Global Change Biology* **22**, 2353–2369 (2016).
31. Fatolazadeh, F. & Goïta, K. Mapping terrestrial water storage changes in Canada using GRACE and GRACE-FO. *Science of The Total Environment* **779**, 146435 (2021).
32. Wang, H. *et al.* Increased water storage in North America and Scandinavia from GRACE gravity data. *Nature Geosci* **6**, 38–42 (2013).
33. Huang, J., Pavlic, G., Rivera, A., Palombi, D. & Smerdon, B. Mapping groundwater storage variations with GRACE: a case study in Alberta, Canada. *Hydrogeol J* **24**, 1663–1680 (2016).
34. Bringeland, S. & Fotopoulos, G. Mass changes in a high-latitude river basin from two decades of GRACE/GRACE-FO. *JGR Earth Surface* **130**, e2024JF008017 (2025).
35. Zhong, Y. *et al.* Reinterpreting global GRACE trends based on century-long GRACE-REC data. *Water Resources Research* **59**, e2023WR035817 (2023).
36. Wang, S. & Li, J. Terrestrial water storage climatology for Canada from GRACE satellite observations in 2002–2014. *Canadian Journal of Remote Sensing* **42**, 190–202 (2016).
37. Li, J. & Wang, S. Seasonal variations and long-term trends of groundwater over the Canadian landmass. *Hydrogeol J* **30**, 401–415 (2022).
38. Baltzer, J. L. *et al.* Overwintering fires can occur in both peatlands and upland forests with varying ecological impacts. *Nat Ecol Evol* **9**, 559–564 (2025).

39. Scholten, R. C., Jandt, R., Miller, E. A., Rogers, B. M. & Veraverbeke, S. Overwintering fires in boreal forests. *Nature* **593**, 399–404 (2021).
40. Xu, W., Scholten, R. C., Hessilt, T. D., Liu, Y. & Veraverbeke, S. Overwintering fires rising in eastern Siberia. *Environmental Research Letters* **17**, 045005 (2022).
41. Mukhtar, A. Canada wildfires never stopped, they just went underground as ‘zombie fires’ smolder on through the winter. *CBS News* (2024).
42. Miralles, D. G., Gentile, P., Seneviratne, S. I. & Teuling, A. J. Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. *Annals of the New York Academy of Sciences* **1436**, 19–35 (2019).
43. Gloege, L. *et al.* Land-atmosphere cascade fueled the 2020 Siberian heatwave. 1–16 (2020) doi:10.1029/2021AV000619.
44. Bartusek, S., Kornhuber, K. & Ting, M. 2021 North American heatwave amplified by climate-change-driven nonlinear interactions. *Nature Climate Change* (2022).
45. Seneviratne, S. I. *et al.* Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews* **99**, 125–161 (2010).
46. Hagemann, S., Blome, T., Ekici, A. & Beer, C. Soil-frost-enabled soil-moisture–precipitation feedback over northern high latitudes. *Earth Syst. Dynam.* **7**, 611–625 (2016).
47. Koster, R. D., Chang, Y., Wang, H. & Schubert, S. D. Impacts of local soil moisture anomalies on the atmospheric circulation and on remote surface meteorological fields during boreal summer: a comprehensive analysis over North America. *Journal of Climate* **29**, 7345–7364 (2016).
48. Miller, D. L. *et al.* Increased photosynthesis during spring drought in energy-limited ecosystems. *Nat Commun* **14**, 7828 (2023).

49. Bastos, A. *et al.* Direct and seasonal legacy effects of the 2018 heat wave and drought on European ecosystem productivity. *Sci. Adv.* **6**, eaba2724 (2020).
50. Lian, X. *et al.* Summer soil drying exacerbated by earlier spring greening of northern vegetation. *Sci. Adv.* **6**, eaax0255 (2020).
51. Xu, X., Riley, W. J., Koven, C. D., Jia, G. & Zhang, X. Earlier leaf-out warms air in the north. *Nat. Clim. Chang.* **10**, 370–375 (2020).
52. Hessilt, T. D. *et al.* Geographically divergent trends in snow disappearance timing and fire ignitions across boreal North America. *Biogeosciences* **21**, 109–129 (2024).
53. Yue, X., Strada, S., Unger, N. & Wang, A. Future inhibition of ecosystem productivity by increasing wildfire pollution over boreal North America. *Atmos. Chem. Phys.* **17**, 13699–13719 (2017).
54. Lu, Z. & Sokolik, I. N. Examining the impact of smoke on frontal clouds and precipitation during the 2002 Yakutsk wildfires using the WRF-Chem-SMOKE model and satellite data. *JGR Atmospheres* **122**, (2017).
55. Scholten, R. C., Veraverbeke, S., Chen, Y. & Randerson, J. T. Spatial variability in Arctic–boreal fire regimes influenced by environmental and human factors. *Nat. Geosci.* **17**, 866–873 (2024).
56. Chen, Y. *et al.* GFED5NRT: Global Fire Emissions Database near-real-time extension. Zenodo <https://doi.org/10.5281/ZENODO.18702700> (2026).
57. Thompson, D. K., Simpson, B. N., Whitman, E., Barber, Q. E. & Parisien, M.-A. Peatland hydrological dynamics as a driver of landscape connectivity and fire activity in the Boreal Plain of Canada. *Forests* **10**, 534 (2019).

58. McCrystall, M. R., Stroeve, J., Serreze, M., Forbes, B. C. & Screen, J. A. New climate models reveal faster and larger increases in Arctic precipitation than previously projected. *Nat Commun* **12**, 6765 (2021).
59. Zhang, X. *et al.* Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. *Nature Clim Change* **3**, 47–51 (2013).
60. Intergovernmental Panel On Climate Change (Ipcc). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2023). doi:10.1017/9781009157896.
61. Bintanja, R. & Selten, F. M. Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. *Nature* **509**, 479–482 (2014).
62. Peterson, B. J. *et al.* Increasing river discharge to the Arctic ocean. *Science* **298**, 2171–2173 (2002).
63. Wu, P., Wood, R. & Stott, P. Human influence on increasing Arctic river discharges. *Geophysical Research Letters* **32**, 2004GL021570 (2005).
64. Linderholm, H. W. *et al.* Arctic hydroclimate variability during the last 2000 years: current understanding and research challenges. *Clim. Past* **14**, 473–514 (2018).
65. Troy, T. J., Sheffield, J. & Wood, E. F. The role of winter precipitation and temperature on northern Eurasian streamflow trends. *J. Geophys. Res.* **117**, 2011JD016208 (2012).
66. Pavelsky, T. M. & Smith, L. C. Intercomparison of four global precipitation data sets and their correlation with increased Eurasian river discharge to the Arctic Ocean. *J. Geophys. Res.* **111**, 2006JD007230 (2006).
67. Field, R. D. *et al.* A fire-driven shift in Canadian air quality concerns mirrors trends in the US. *Earth's Future* **13**, e2025EF007041 (2025).

68. Lawson, B. D. & Armitage, O. B. *Weather guide for the Canadian Forest Fire Danger Rating System*. (2008).
69. Field, R. D. *et al.* Development of a Global Fire Weather Database. *Nat. Hazards Earth Syst. Sci.* **15**, 1407–1423 (2015).
70. McElhinny, M., Beckers, J. F., Hanes, C., Flannigan, M. & Jain, P. A high-resolution reanalysis of global fire weather from 1979 to 2018 - Overwintering the Drought Code. *Earth System Science Data* **12**, 1823–1833 (2020).
71. Hanes, C. C. *et al.* Evaluation of new methods for drought estimation in the Canadian Forest Fire Danger Rating System. *International Journal of Wildland Fire* **32**, 836–853 (2023).
72. Elder, M., Phillips, C. A., Potter, S., Frumhoff, P. C. & Rogers, B. M. The costs and benefits of fire management for carbon mitigation in Alaska through 2100. *Environ. Res. Lett.* **17**, 105001 (2022).
73. Phillips, C. A. *et al.* Escalating carbon emissions from North American boreal forest wildfires and the climate mitigation potential of fire management. *Science Advances* **8**, 1–10 (2022).
74. Walker, X. J. *et al.* Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature* **572**, 520–523 (2019).
75. Johnstone, J. *et al.* Postfire seed rain of black spruce, a semiserotinous conifer, in forests of interior Alaska. *Can. J. For. Res.* **39**, 1575–1588 (2009).
76. Zhao, J. *et al.* Forest fire size amplifies postfire land surface warming. *Nature* **633**, 828–834 (2024).
77. Wang, W. *et al.* Canadian forests are more conducive to high-severity fires in recent decades. *Science* **387**, 91–97 (2025).

78. Boulanger, Y. *et al.* The 2023 wildfire season in Québec: an overview of extreme conditions, impacts, lessons learned, and considerations for the future. *Can. J. For. Res.* **55**, 1–21 (2025).
79. Christianson, A. C. *et al.* Wildland fire evacuations in Canada from 1980 to 2021. *International Journal of Wildland Fire* **33**, WF23097 (2024).
80. Nelson, J. L., Zavaleta, E. S. & Chapin, F. S. Boreal fire effects on subsistence resources in Alaska and adjacent Canada. *Ecosystems* **11**, 156–171 (2008).
81. Wang, Z. *et al.* Severe global environmental issues caused by Canada’s record-breaking wildfires in 2023. *Adv. Atmos. Sci.* **41**, 565–571 (2024).
82. Yu, M., Zhang, S., Ning, H., Li, Z. & Zhang, K. Assessing the 2023 Canadian wildfire smoke impact in Northeastern US: Air quality, exposure and environmental justice. *Science of The Total Environment* **926**, 171853 (2024).
83. Chen, Y. *et al.* Tracking recent extremes and interannual variability of global fire emissions using a near-real-time extension to the Global Fire Emissions Database. Preprint at <https://doi.org/10.5194/essd-2026-158> (2026).
84. Chen, Y. *et al.* Multi-decadal trends and variability in burned area from the fifth version of the Global Fire Emissions Database (GFED5). *Earth System Science Data* **15**, 5227–5259 (2023).
85. Van Der Werf, G. R. *et al.* Landscape fire emissions from the 5th version of the Global Fire Emissions Database (GFED5). *Sci Data* **12**, 1870 (2025).
86. Scholten, R. C., Chen, Y., Veraverbeke, S. & Randerson, J. T. Arctic-boreal fire atlas: 12-hourly perimeters of individual fires in the Arctic-boreal domain from 2012 to 2023 [dataset]. PANGAEA <https://doi.org/10.1594/PANGAEA.967653> (2024).

87. Zhizhin, M. *et al.* Measuring gas flaring in Russia with multispectral viirs nightfire. *Remote Sensing* **13**, 3078 (2021).
88. Elvidge, C. D., Zhizhin, M., Baugh, K., Hsu, F. C. & Ghosh, T. Methods for global survey of natural gas flaring from visible infrared imaging radiometer suite data. *Energies* **9**, (2016).
89. Hall, R. J. *et al.* Generating annual estimates of forest fire disturbance in Canada: The National Burned Area Composite. *International Journal of Wildland Fire* **29**, 878–891 (2020).
90. Skakun, R., Castilla, G. & Jain, P. Mapping wildfires in Canada with Landsat MSS to extend the National Burned Area Composite (NBAC) time series back to 1972. *International Journal of Wildland Fire* **33**, WF24138 (2024).
91. Ghobadi-Far, K. *et al.* The impact of new accelerometer transplant data (ACH) on GRACE Follow-On along-orbit inter-satellite laser ranging observations and monthly time-variable gravity and mascon solutions. *JGR Solid Earth* **128**, e2023JB026740 (2023).
92. Bandikova, T., McCullough, C., Kruizinga, G. L., Save, H. & Christophe, B. GRACE accelerometer data transplant. *Advances in Space Research* **64**, 623–644 (2019).
93. Tapley, B. D. *et al.* Contributions of GRACE to understanding climate change. *Nat. Clim. Chang.* **9**, 358–369 (2019).
94. Landerer, F. W. *et al.* Extending the global mass change data record: GRACE Follow-On instrument and science data performance. *Geophysical Research Letters* **47**, e2020GL088306 (2020).
95. Richard Peltier, W., Argus, D. F. & Drummond, R. Comment on “An assessment of the ICE-6G_C (VM5a) glacial isostatic adjustment model” by Purcell *et al.* *JGR Solid Earth* **123**, 2019–2028 (2018).

96. Adler, R. F. *et al.* The Version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–Present). *J. Hydrometeor* **4**, 1147–1167 (2003).
97. Miralles, D. G. *et al.* GLEAM4: global land evaporation and soil moisture dataset at 0.1° resolution from 1980 to near present. *Sci Data* **12**, 416 (2025).
98. Monteith, J. L. & Unsworth, M. H. *Principles of Environmental Physics: Plants, Animals, and the Atmosphere*. (AP, Amsterdam, 2013).
99. Badgley, G., Anderegg, L. D. L., Berry, J. A. & Field, C. B. Terrestrial gross primary production: Using NIR_v to scale from site to globe. *Global Change Biology* **25**, 3731–3740 (2019).
100. Schaaf, C., Wang, Z., Zhang, X. & Strahler, A. VIIRS/NPP BRDF/Albedo Nadir BRDF-Adjusted Ref Daily L3 Global 500m SIN Grid V001. NASA Land Processes Distributed Active Archive Center <https://doi.org/10.5067/VIIRS/VNP43IA4.001> (2018).
101. Pawson, S. MERRA-2 tavg1_2d_lfo_Nx: 2d,1-Hourly,Time-Averaged,Single-Level,Assimilation,Land Surface Forcings V5.12.4. NASA Goddard Earth Sciences Data and Information Services Center <https://doi.org/10.5067/L0T5GEG1NYFA> (2020).
102. Kim, J. E. Understanding the influence of fire on photosynthesis in North American Arctic-boreal ecosystems. (University of California Irvine, Irvine, 2025). doi:ProQuest ID: Kim_uci_0030D_19615. Merritt ID: ark:/13030/m5d913j0.
103. Pastorello, G. *et al.* The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data. *Sci Data* **7**, 225 (2020).
104. Byrd, R. H., Lu, P., Nocedal, J. & Zhu, C. A Limited memory algorithm for bound constrained optimization. *SIAM J. Sci. Comput.* **16**, 1190–1208 (1995).
105. Williams, A. P. *et al.* Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future* **7**, 892–910 (2019).

106. Hessilt, T. D. *et al.* Future increases in lightning ignition efficiency and wildfire occurrence expected from drier fuels in boreal forest ecosystems of western North America. *Environmental Research Letters* **17**, (2022).
107. Scholten, R. C. *et al.* Multi-ignition fire complexes drive extreme fire years and impacts. *Sci. Adv.* **12**, eadx6477 (2026).

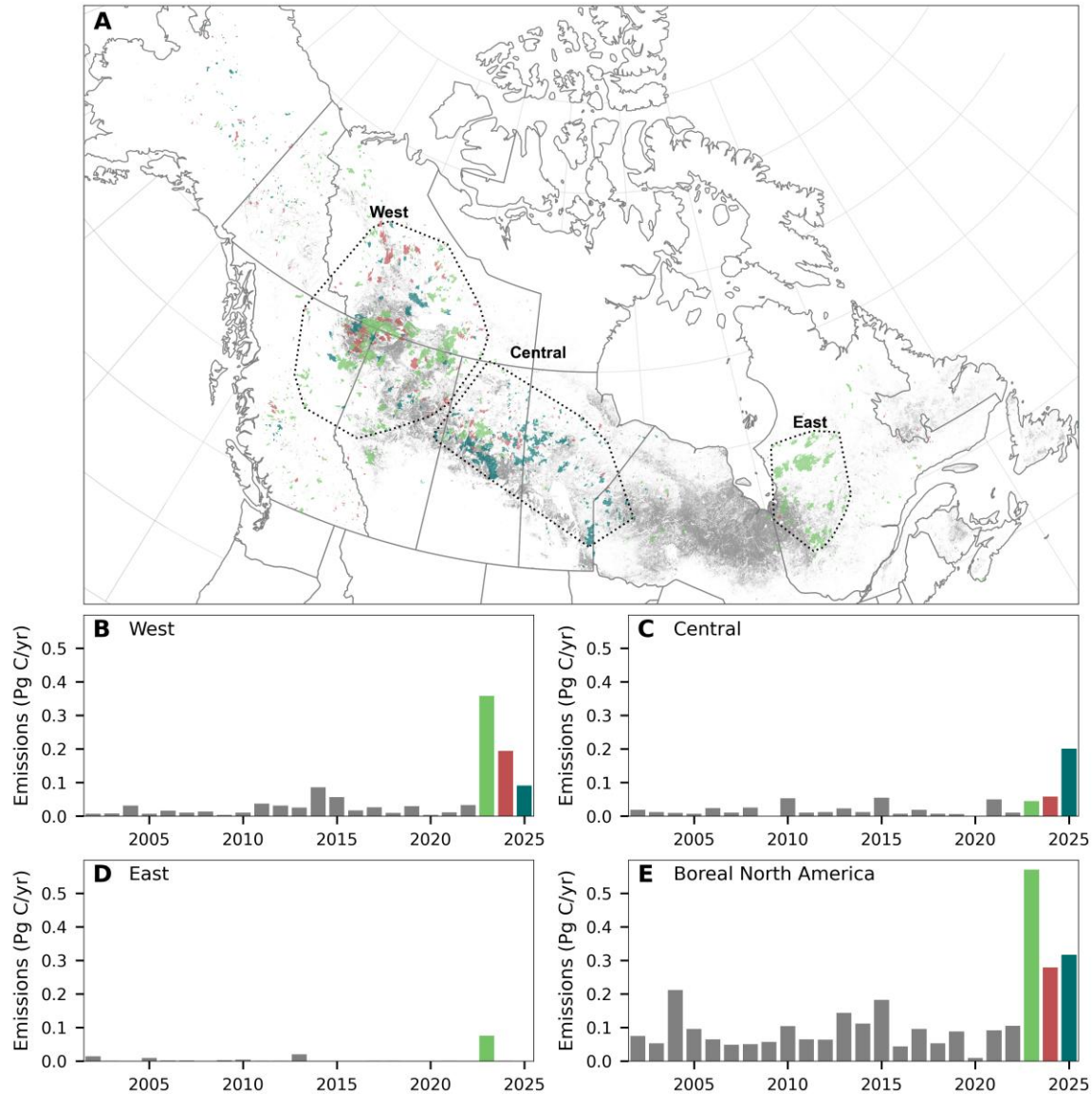


Fig. 1. Burned area and carbon emissions during three consecutive extreme fire seasons in boreal North America (2023–2025). (A) Map of fire perimeters in Canada and Alaska during 2023–2025 derived from the Arctic-Boreal Fire Atlas. Fire perimeters from 2023, 2024, and 2025 are shown in green, red, and blue, respectively. Dashed black polygons delineate three high-burning regions in western, central, and eastern Canada. Gray shading indicates the distribution of Canadian peatlands (57). (B–E) Time series of fire carbon emissions from GFED5 for the three high-fire regions and for the full boreal North America domain.

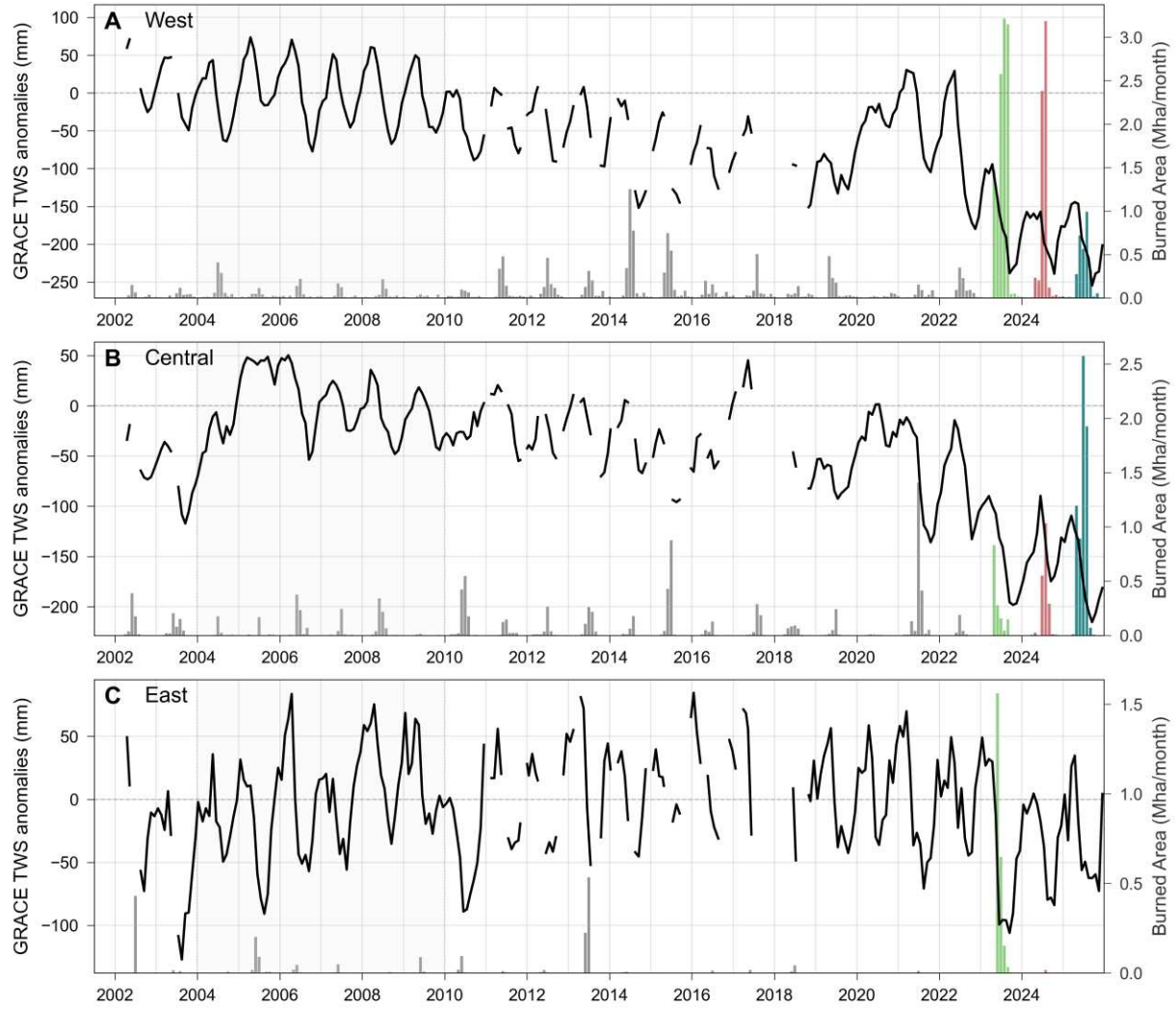


Fig. 2. Persistent terrestrial water storage deficits precede and accompany extreme wildfire activity in Canada. Time series of terrestrial water storage (TWS) anomalies from the Gravity Recovery and Climate Experiment (GRACE) satellites (black lines) and monthly burned area from GFED5 (bars) for the western (A), central (B), and eastern (C) high-fire regions outlined in Fig. 1A. Periods of sustained negative TWS anomalies coincide with the onset and persistence of large burned-area events, consistent with hydrological drought preconditioning landscapes for extreme fire activity. Gray shaded areas (2004–2009) represent the baseline period used for computing TWS anomalies in the GRACE RL06Mv04 product.

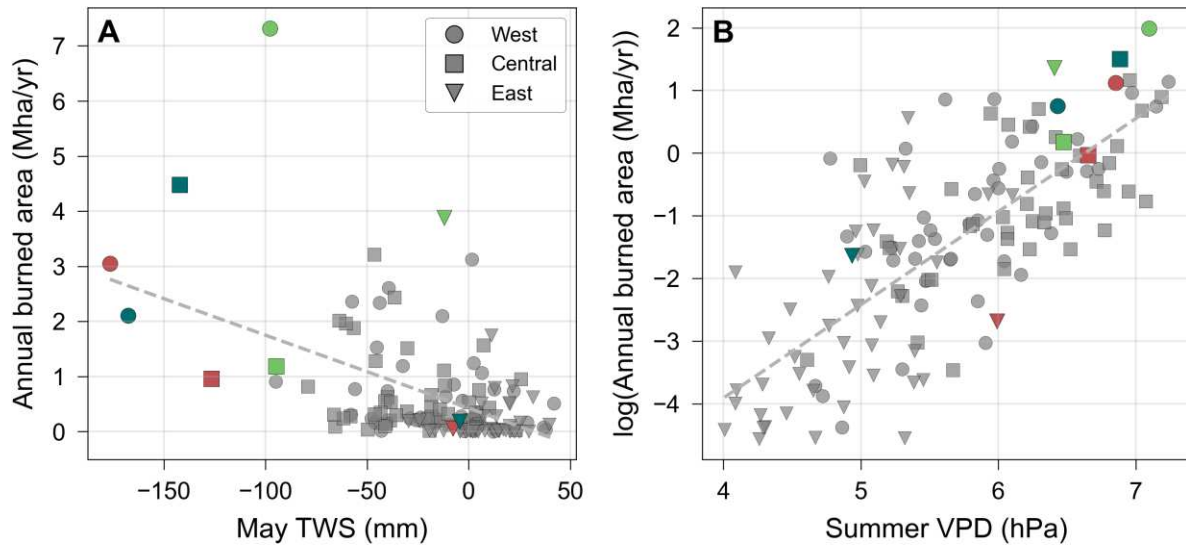


Fig. 3. Terrestrial water storage anomalies and vapor pressure deficit are strong predictors of burned area in boreal North America. (A) Relationship between modeled May terrestrial water storage anomalies (TWS), derived from GRACE, and annual burned area from Canada's National Burned Area Composite (NBAC) dataset across three high-fire regions for 1980–2025 ($r = -0.50$, $p < 0.001$). (B) Relationship between mean summer (June–August) vapor pressure deficit (VPD) and the logarithm of annual burned area ($r = 0.76$, $p < 0.001$). Data for 2023, 2024, and 2025 are shown in green, red, and blue, respectively. Relationships disaggregated by individual region are shown in fig. S5.

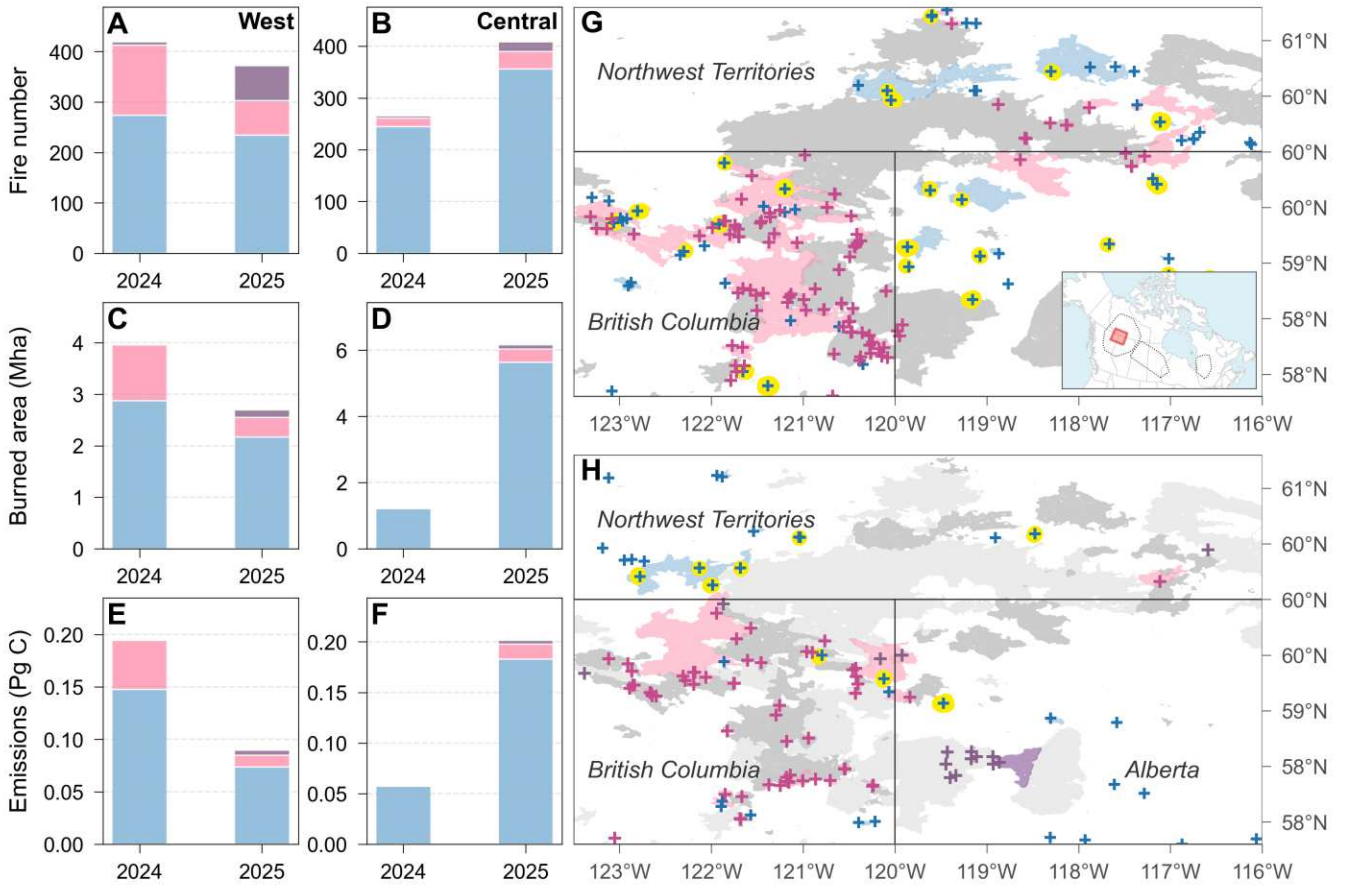


Fig. 4. Overwintering fires in western and central Canada and their contribution to burned area and carbon emissions. (A, B) Number of fires, (C, D) burned area, and (E, F) carbon emissions for recent hotspots of fire activity in western and central Canada. We do not show panels for the eastern region since overwintering fires had a negligible effect ($< 1\%$) on emissions. Burned area contributions were computed by tracking the merging of multiple ignitions within each fire and splitting the burned area of merged fires evenly between fires for each time step; emission contributions were derived by applying burned area contributions to 0.25° GFED grid cells. Absolute and relative totals are listed in table S6. (G, H) Maps of burned area and ignitions in western Canada in 2024 (G) and 2025 (H). Dark gray: burned area from the previous year; light gray: two years prior. Blue: burned area from new ignitions; pink: burned area from overwintering fires of the previous year; purple: burned area from overwintering fires two years prior. Perimeters

are colored pink or purple if at least one ignition (+ symbols) falls within a 1-km buffer of the prior year's burned area. Yellow points indicate lightning strikes from the Canadian Lightning Detection Network up to 5 days before a recorded ignition.

Materials and Methods

Fire data

We used four datasets of annual burned area. Datasets based on medium-resolution satellite imagery (375–1000m) were used to derive fire ignitions, daily perimeters, and fire emissions. To extend the fire record back in time, we supplemented these with historical government fire perimeter records for Canada and Alaska. While the government datasets provide higher spatial resolution and a longer temporal record, they do not include ignitions, daily perimeters, or emissions estimates. Medium-resolution satellite products may over- or underestimate burned area due to their coarser spatial resolution and inability to explicitly map unburned islands within fire perimeters. However, comparison across datasets demonstrated that interannual variability in burned area is well captured by medium-resolution satellite datasets, indicating that these uncertainties have minimal impact on our analysis.

Burned area and emissions data from 2002 to 2025 were taken from the Global Fire Emissions Database version 5 (GFED5), supplemented with the GFED near-real-time extension for the years 2023–2025⁸³. GFED combines satellite information on fire activity and vegetation productivity to estimate gridded monthly burned area and fire emissions at 0.25° resolution^{84,85}. We excluded burned area and emissions from cropland areas. At annual scale, GFED burned area was highly correlated with governmental records ($R=0.97$, $p < 0.001$).

Daily burned area and ignition locations from 2012 to 2025 were obtained from an updated version of the Arctic-Boreal Fire Atlas (ABFA), an individual fire event database for the circumpolar Arctic-boreal domain⁸⁶. ABFA provides ignition locations and 12-hourly fire perimeters derived from 375 m Visible Infrared Imaging Radiometer Suite (VIIRS) active fire detections using an Arctic-boreal specific fire tracking algorithm designed to handle large fires with fragmented detections, long smoldering times, and landscapes fragmented by water bodies.

For the updated version, we combined active fire data (Collection 2.4) from the Suomi National Polar-orbiting Partnership (Suomi NPP) and National Oceanic and Atmospheric Administration – 20 (NOAA-20) satellites. We applied three filtering steps to ABFA ignition and fire perimeter data from 2012-2025 to maintain a high-quality wildfire dataset. First, we excluded fires with more than 5% of their area overlapping agricultural land. For determining agricultural lands, we used the 2023 Canadian Annual Crop Inventory for Canada and the National Land Cover Database (NLCD) 2016 for Alaska (classes 81 and 82). We further removed ignitions that intersected with known gas flare locations^{87,88}. To remove slash burns, which are prevalent in British Columbia and Alberta in winter, we removed all fires that started in the months October to April. We retained fires occurring in January–March only if they originated within 1000 m of the edge of a previous burn perimeter (see Methods section on overwintering fire identification) to keep potential early overwintering fires in the record. This filtering routine retained 22,192 of the initial 104,507 ABFA perimeters, and 91% (70.9 Mha) of the burned area in 2012-2025. The interannual variation in burned area from ABFA was in good agreement with governmental records ($R=0.99$, $p < 0.001$).

Government records of fire perimeters from 1985 to 2025 were obtained from the National Burned Area Composite (NBAC) for Canada^{89,90} and the Alaska Wildland Fire Maps (AWFM) for Alaska. NBAC perimeters are compiled annually since 1972 by the FireMARS system and are based on data from Natural Resources Canada and Provincial, Territorial, and Parks Canada agencies, as well as Landsat imagery. AWFM data are provided by the Alaska Interagency Coordination Center and the Bureau of Land Management and contain all wildfires with perimeters of at least 100 acres since 1987, and perimeters of at least 10 acres since 2016. AWFM perimeters are based on hand sketched perimeters drawn on topographic maps or interpretation of fine scale satellite imagery such as 10-m Sentinel-2 imagery.

Climate and drought data

As an indicator for drought, we used terrestrial water storage (TWS) anomalies from the Gravity Recovery and Climate Experiment (GRACE) and Follow-On (GRACE-FO) satellites available from April 2002 to October 2025, which have several gaps due to decommissioning between GRACE and GRACE-FO missions (June 2017 to May 2018), as well as battery management periods and instrument issues^{91–94}. We used the GRACE Level-3 gridded land fields which include monthly liquid water equivalent thickness processed by the Jet Propulsion Laboratory (JPL) based on the JPL RL06M Mascon solution version 04 (RL06Mv04) with the Coastal Resolution Improvement (CRI) filter applied. These data are provided on a 0.5-degree global grid derived from 3-degree equal-area mass concentration (mascon) blocks. Anomalies are calculated relative to the baseline time-mean (2004–2009) and have been corrected for glacial isostatic adjustment (GIA) using the ICE6G-D model⁹⁵. The dataset includes scale factors to restore signal amplitude reduced by the GRACE de-stripping and smoothing processes.

To reconstruct and decompose the GRACE signal from 1980 to 2025, we used precipitation records from the Global Precipitation Climatology Project (GPCP) Monthly Analysis Product⁹⁶ and monthly actual evaporation data from the Global Land Evaporation Amsterdam Model (GLEAM) version 4.2a⁹⁷ as well as a fitted loss term for runoff. GPCP integrates multiple satellite-based rainfall estimates with rain gauge station data to provide consistent global precipitation analyses. These data are provided on a 2.5-degree global grid covering 88.75°N to 88.75°S. GLEAM provides global estimates of actual evapotranspiration based on satellite observations of soil moisture, vegetation optical depth, and snow water equivalent, combined with reanalysis air temperature and radiation data. The algorithm uses a Priestley-Taylor equation and applies a series of stress factors to account for limitations in evaporation due to moisture availability and vegetation dynamics. GLEAM v4.2 data for 1980–2024 are provided annually on a 0.25-degree global grid and include separate estimates for transpiration, bare-soil evaporation, interception

loss, open-water evaporation, and sublimation. In our analysis, we used the actual evaporation estimate, which is the sum of all of these components. To extend the evaporation record for 2025, we leveraged the relationship between GLEAM evaporation and vapor pressure deficit derived from fifth-generation European Centre for Medium-Range Weather Forecasts Reanalysis Land (ERA5-Land) reanalysis products. We developed region-specific linear regression models predicting monthly evaporation from monthly mean VPD for each study region. We developed region-specific linear regression models predicting monthly evaporation from monthly mean VPD, grouping months into five periods (June–July, August, September, October, and all other months) to account for seasonal variation in the ET-VPD relationship. VPD models were trained on monthly data from 1980–2024 and achieved high predictive performance across all three study regions ($R^2 = 0.96\text{--}0.98$).

Vapor pressure deficit (VPD) was derived from ERA5-Land based on 2-m air temperature and 2-m dewpoint temperature. Daily mean records for 1980–2025 were downloaded from the Copernicus Climate Data Store (CDS) at ERA5-Land's native spatial resolution of approximately 9 km. From these variables, we calculated saturated vapor pressure (e_s) and actual vapor pressure (e_a) following the Tetens formulation⁹⁸:

$$e_s = 6.1078 \times \exp \frac{17.2694 \times (T-273.16)}{(T-35.86)} \text{ (hPa)} \quad (1)$$

where T represents surface air temperature in Kelvin. Actual vapor pressure (e_a) was computed by substituting dewpoint temperature for T in the same equation. Daily VPD was then determined as the difference between e_s and e_a . Monthly VPD values were calculated by averaging the daily VPD estimates within each month.

To contextualize the severity of recent drought conditions relative to the historical record, we used September TWS as a reference month for annual water storage minima. We chose September

because it represents the most frequently observed seasonal low point of terrestrial water storage across Canadian boreal regions. We extracted modeled September TWS values from the reconstruction for the western, central, and eastern regions for each year from 1980 to 2025 and computed kernel density estimates from the pre-2023 period (1980–2022) to characterize the historical distribution of end-of-summer water storage (fig. S4). The position of 2023–2025 values relative to these modelled distributions illustrates the exceptional nature of the drought conditions preceding and concurrent with the recent fire extremes.

Gross primary productivity data

Daily gross primary production (GPP, $\text{gC m}^{-2} \text{ day}^{-1}$) at 0.25-degree resolution was modeled using near-infrared reflectance of vegetation (NIRv)⁹⁹ calculated from the VIIRS Nadir Bidirectional Reflectance Distribution Function (BRDF) Adjusted Reflectance (NBAR) surface reflectance product (VNP43IA4)¹⁰⁰ and diffuse and direct photosynthetically active radiation from MERRA-2^{101,102}. We formulate GPP as:

$$GPP = a \times (NIRv - c) \times PAR_{direct} + b \times (NIRv - c) \times PAR_{diffuse} \quad (2)$$

where a and b are direct and diffuse radiation parameters (gC/MJ), and c is a soil correction parameter (unitless). These model parameters were calibrated using the daily GPP (GPP_DT_VUT_MEAN) available from multiple regional eddy covariance networks using the ONEFlux processing pipeline (AmeriFlux, ICOS, FLUXNET2015)¹⁰³. Anomalies are calculated by removing the weekly mean climatology (2012–2021, 10-year average) from associated daily values for each grid cell.

Identification of hotspot regions

To identify regional hotspots of fire activity in boreal North America and define study regions, we selected large fires ($>100 \text{ km}^2$) from 2023–2025 and applied a kernel density estimation (KDE) approach weighted by fire area. Using a 200 km bandwidth Gaussian kernel, we

calculated density scores for each fire polygon based on the spatial distribution of burned area. Fires were then clustered iteratively starting from the highest-density areas, with clusters defined by a 50 km search radius around seed polygons, until approximately 90% of the total burned area was covered. To reduce the spatial complexity and group geographically proximate fire clusters, we applied k-means clustering (k=3) to the centroids of the density-based clusters, resulting in three broad regions: West, Central, and East (Fig. 1A). The West region is roughly centered at the intersection between British Columbia, Alberta, and the Northwest Territories; the Central region includes the majority of boreal Saskatchewan and Manitoba, and the East region covers a large fraction of western Québec. Final region boundaries were defined as the convex hulls of the fires within each k-means cluster, capturing the primary areas of fire activity during the recent extreme fire years. The final regions comprised 82% of the total burned area in Canada and Alaska in 2023–2025, and 67% of the total burned area in 2012–2025.

GRACE reconstruction

To provide a longer-term perspective on drought conditions and to decompose TWS trends into their driving components, we reconstructed GRACE TWS anomalies back to 1980 using monthly precipitation from GPCP and monthly actual evapotranspiration from GLEAM. The reconstruction was performed separately for three regions (West, Central, and East). We employed a simple water balance model that simulates monthly TWS changes as a function of precipitation inputs, evapotranspiration outputs, and a loss term representing runoff and deep drainage:

$$\frac{dTWS}{dt} = a * P + b * E - \frac{TWS}{\tau_D} \quad (3)$$

where TWS is the monthly average terrestrial water storage anomaly (mm/d), P is the monthly average precipitation (mm/d), E is the monthly average actual evapotranspiration (mm/d), and a, b, and τ_D are calibrated parameters. The parameter τ_D represents a monthly fractional loss rate

(drainage term), while a and b are scaling coefficients that convert daily precipitation and evapotranspiration fluxes to changes in water storage at a monthly time interval, accounting for uncertainties in the data, generating a P-E term that most closely tracks TWS changes. To match the roughly mid-month observations from GRACE, we used the mean of the current and previous months for precipitation and evapotranspiration inputs. A fourth parameter, the initial storage value, was calibrated to align the reconstruction with the GRACE observations at the start of the satellite record in April 2002. Parameters were optimized separately for each region by minimizing the root mean square error (RMSE) between the simulated and observed GRACE TWS anomalies over the entire GRACE/GRACE-FO period (April 2002 to December 2025) using the L-BFGS-B algorithm¹⁰⁴. The optimization was constrained to physically realistic values (c bounded between 0 and 1 to ensure storage decay without artificial accumulation). The fitted coefficients for the three regions and associated performance metrics are listed in table S2 and time series of modelled and observed TWS for the three regions are shown in fig. S2.

To decompose the TWS signal and identify the relative contributions of precipitation versus evapotranspiration variability, we conducted two additional reconstruction experiments for each region in addition to the full-forcing simulation using observed monthly precipitation and evapotranspiration. First, we used observed precipitation but replaced actual ET with long-term monthly climatological means (1980-2025), thereby isolating the effect of precipitation variability. Second, we used observed evapotranspiration but replaced actual precipitation with long-term monthly climatological means, thereby isolating the effect of ET variability. By comparing these simulations, we could quantify whether observed TWS trends and anomalies were driven primarily by precipitation deficits or evapotranspiration increases. To quantify the relative contribution of each driver to recent drought conditions, we calculated the mean TWS for a baseline period (2002-2012) and the large fire years (2023-2025) for each simulation, and computed the deficit as the

difference between recent and baseline means. The percentage contribution of precipitation variability (ET-climatology simulation) and evapotranspiration variability (precipitation-climatology simulation) to the total deficit was determined by dividing each component's deficit by the full-model deficit (table S3).

Regression models for burned area

To assess the unique contributions of spring water deficit and summer VPD to annual burned area, we fit exponential regression models to regional fire activity data for 1980–2025. We focused our analysis on the three hotspot regions of fire activity (Fig. 1A) and used burned area from NBAC as the dependent variable. The modelled terrestrial water storage anomaly for the month of May served as a measure for the spring soil moisture status, and the average VPD across the summer months (June, July and August) as a measure for fire-prone weather in summer. We tested two model formulations: a vapor pressure deficit (VPD) only model:

$$BA = a + b \cdot e^{c \cdot VPD}, \quad (4)$$

and a combined model incorporating both May TWS and VPD:

$$BA = a + b \cdot e^{c \cdot VPD} + d \cdot TWS_{May}, \quad (5)$$

where BA is annual burned area in millions of hectares. The exponential form for VPD was chosen to reflect the logarithmic relationship with burned area shown in Fig. 3 and as reported by Williams et al. for the western US¹⁰⁵. Both TWS and VPD were normalized (z-scores) prior to fitting. Models were fit using non-linear least squares optimization.

Model performance was evaluated using multiple metrics (table S4): coefficient of determination (R^2), adjusted R^2 (accounting for number of parameters), root mean square error (RMSE), mean absolute error (MAE), Akaike Information Criterion (AIC), and Bayesian

Information Criterion (BIC). This approach was applied separately to each of the three regional fire hotspots.

Overwintering identification and burned area attribution

To identify potential overwintering fires, we spatially intersected each year's ignitions from ABFA with a buffer of 1 km around fire perimeters from the previous two years following³⁹. For the burn edge we used the final perimeter reported by NBAC and AWFM, since these data provide a more accurate estimate of the final perimeter than ABFA. We also computed the time since the previous fire (1 or 2 years) and individual ignition characteristics including the maximum area reached before merging or extinction, and the number of individual growth intervals. We used lightning location and timing data from the Canadian Lightning Detection Network²¹ to remove potential overwintering fires that spatially intersected with a recorded lightning strike up to five days¹⁰⁶ before the detected ignition. We buffered lightning strike locations by 2.5 km to account for location uncertainty of the dataset. This buffer distance is conservative, since the reported location uncertainty is less than 250 m for the majority of the recorded lightning strikes. The total number of potential overwintering fires that overlapped with a recorded lightning strike was low (34 fires in 2024, and 16 fires in 2025), and even increasing the temporal threshold to the beginning of the respective year had only marginal effects (1–2%) on the total contributions of these fires to total burned area and carbon emissions across boreal North America.

For multi-ignition fires where multiple ignitions eventually merged into a single large fire complex, we developed an area attribution algorithm to estimate the contribution of each ignition (including overwintering ignitions) to the final burned area. This attribution allowed us to quantify the specific contribution of overwintering ignitions to large fire complexes that also included subsequent lightning-ignited fires.

First, we applied a filter to all ignitions within multi-ignition fires to remove features that resemble fire starts, including spot fires, back-burns ignited for fire management purposes, or artifacts created by detection gaps (for example, because of dense clouds or smoke) by combining the ignition filtering criteria established in¹⁰⁷ and³⁹. This filtering routine only retains ignitions that meet at least one of the following criteria: 1) ignitions that occurred on the first day of fire activity, 2) ignitions that grew to at least 1 km² and experienced at least one growth interval before merging with the main fire, or 3) ignitions that occurred within a 1 km of the burn edge of a previous fire (as explained above).

ABFA only outputs perimeters when new active fire detections occur for an individual fire which can lead to artificial variability (shrinking and growing) in growth trajectories, especially in the case of complex fire merging histories. To consistently track fire growth, we therefore first gap-filled the perimeter time series by carrying forward the last known perimeter for each fire until a new perimeter was detected or the fire merged with another fire.

We then processed each fire's merge events in chronological order to assess the burned area contributions of each ignition. At each merge event, we calculated the area growth of the target fire since its last merge, then distributed this growth equally among all ignitions that had contributed to that fire up to that point. After the final merge, remaining area growth was distributed among all contributing ignitions. This approach assumes that once fires merge, their subsequent growth is equally attributable to all contributing ignitions.

Acknowledgments: Anthropic Claude Sonnet (version 4.6) was used for copyediting on early drafts of select paragraphs, for initial guidance on the optimization of the water balance model, and for assistance with figure formatting for journal style guidelines. All authors have reviewed, edited, and approved the final text of this manuscript.

Funding: This research was funded through a Dutch Research Council (NWO) Rubicon Grant (019.241EN.018) to RCS. JTR, DCM and RF acknowledge funding from NASA Earth Information System – Fire (80NSSC20K0590) and NASA FireSense (80NSSC24K1823 and 80NSSC24K1317). JTR acknowledges support from NASA Carbon Monitoring System (80NSSC24K0301), US National Science Foundation Collaborations in Artificial Intelligence and Geosciences grant RISE-2425932, and US Dept of Energy Office of Science Biological and Environmental Research E3SM and RUBISCO Science Focus Areas. BMR acknowledges support from the Gordon and Betty Moore Foundation, Google.org, the McCall MacBain Foundation, and funding catalyzed through the TED Audacious Project (Permafrost Pathways).

Author contributions:

Conceptualization: RCS, JTR

Methodology: RCS, RF, YC, JTR

Investigation: RCS, JEK, RF, YC

Visualization: RCS

Writing – original draft: RCS

Writing – review & editing: All authors

Competing interests: All authors declare they have no competing interests.

Data, code, and materials availability: AWFM data are provided by the Alaska Interagency Coordination Center and Bureau of Land management (<https://fire.ak.blm.gov/predsvcs/maps.php>). NBAC data can be downloaded from the CWFIS Datamart (<https://cwfis.cfs.nrcan.gc.ca/datamart/metadata/nbac>). GFED5 data can be accessed from <https://www.globalfiredata.org/data.html>. GRACE data were downloaded from the JPL

GRACE Tellus website (<https://grace.jpl.nasa.gov>). GPCP data were downloaded from the NOAA Physical Sciences Laboratory (PSL) (<https://psl.noaa.gov/data/gridded/data.gpcp.html>). GLEAM data can be accessed from <https://www.gleam.eu/>. Daily ERA5-land data can be downloaded from the Copernicus Data Storage (<https://cds.climate.copernicus.eu/datasets/derived-era5-land-daily-statistics>). 2016 NLCD data for Alaska is available from the Multi-Resolution Land Characteristics Consortium (<https://www.mrlc.gov/data>). 2023 Canadian Annual Crop Inventory data is available from the Earth Observation Team of Agriculture and Agri-Food Canada (AAFC) (<https://open.canada.ca/data/en/dataset/5d3ab93e-324a-41db-8d29-0f0813d0e9cd>). Annual gas flare locations are extracted by the Earth Observation Group, Payne Institute for Public Policy (https://eogdata.mines.edu/products/vnf/global_gas_flare.html). Peatland extend for Canada was taken from <https://open.canada.ca/data/en/dataset/62d63169-7739-4515-9178-8f628c32a9d4>. The VIIRS NBAR surface reflectance product VNP43IA4 V002 data files are available in the LP DAAC stored and accessed through the NASA EARTHDATA search at <https://doi.org/10.5067/VIIRS/VNP43IA4.002>. The MCD12Q1v061 is available on the LP DAAC at <https://doi.org/10.5067/MODIS/MCD12Q1.061>. MERRA-2 datasets are available in NASA's Goddard Earth Sciences and Information Services Center (GES DISC). Photosynthetically active radiation from the M2T1NXLFO product can be found at <https://doi.org/10.5067/L0T5GEG1NYFA>.

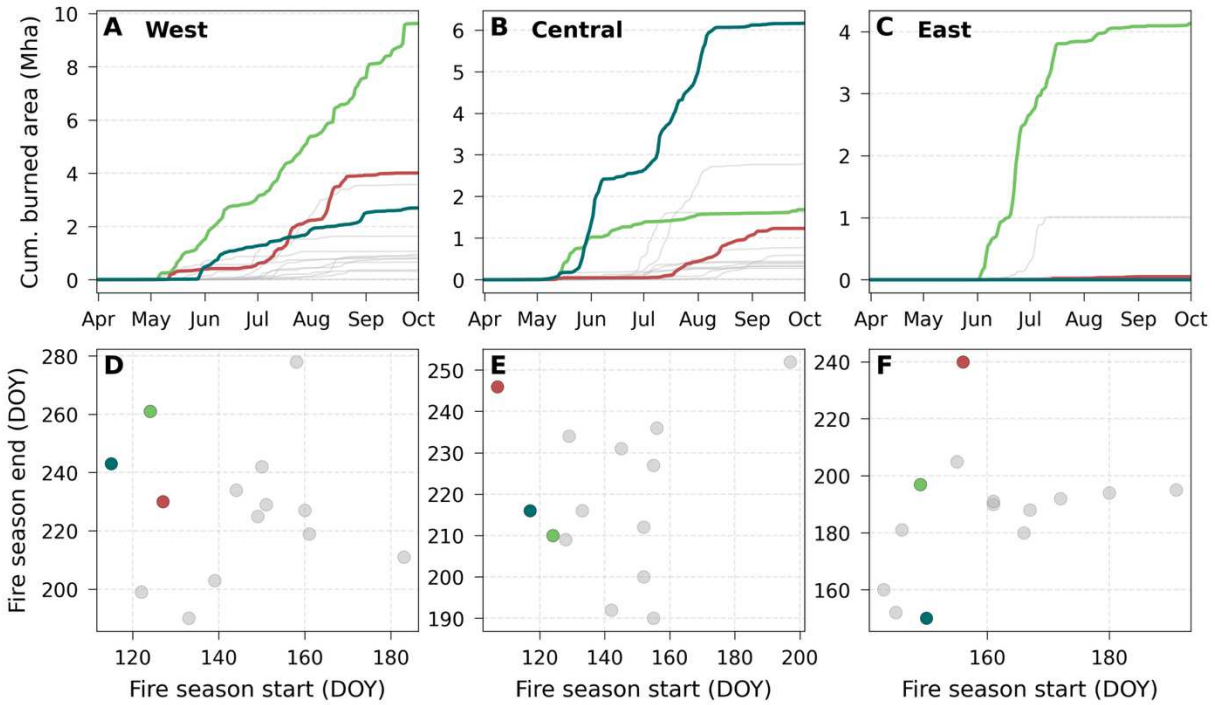


Fig. S1: Characteristics of the 2023–2025 fire seasons compared to 2012–2022 in the three hotspot regions. A-C, Cumulative daily burned area during the fire season (April 1 – October 1) for hotspot regions in boreal North America in 2021–2022 (grey lines) and in 2023 (green), 2024 (red) and 2025 (blue). D-F, Day of year of fire season start (when cumulative burned area is 1% of the multi-year median total burned area per region) and end (when 90% of annual burned area had occurred). The 1% burned area cutoffs are 95.3 km² for West, 51.3 km² for Central and 1.2 km² for East. All data are based on the Arctic-boreal fire atlas (ABFA) which deploys 12-hourly aggregation of Suomi-NPP and NOAA-20 VIIRS active fire data.

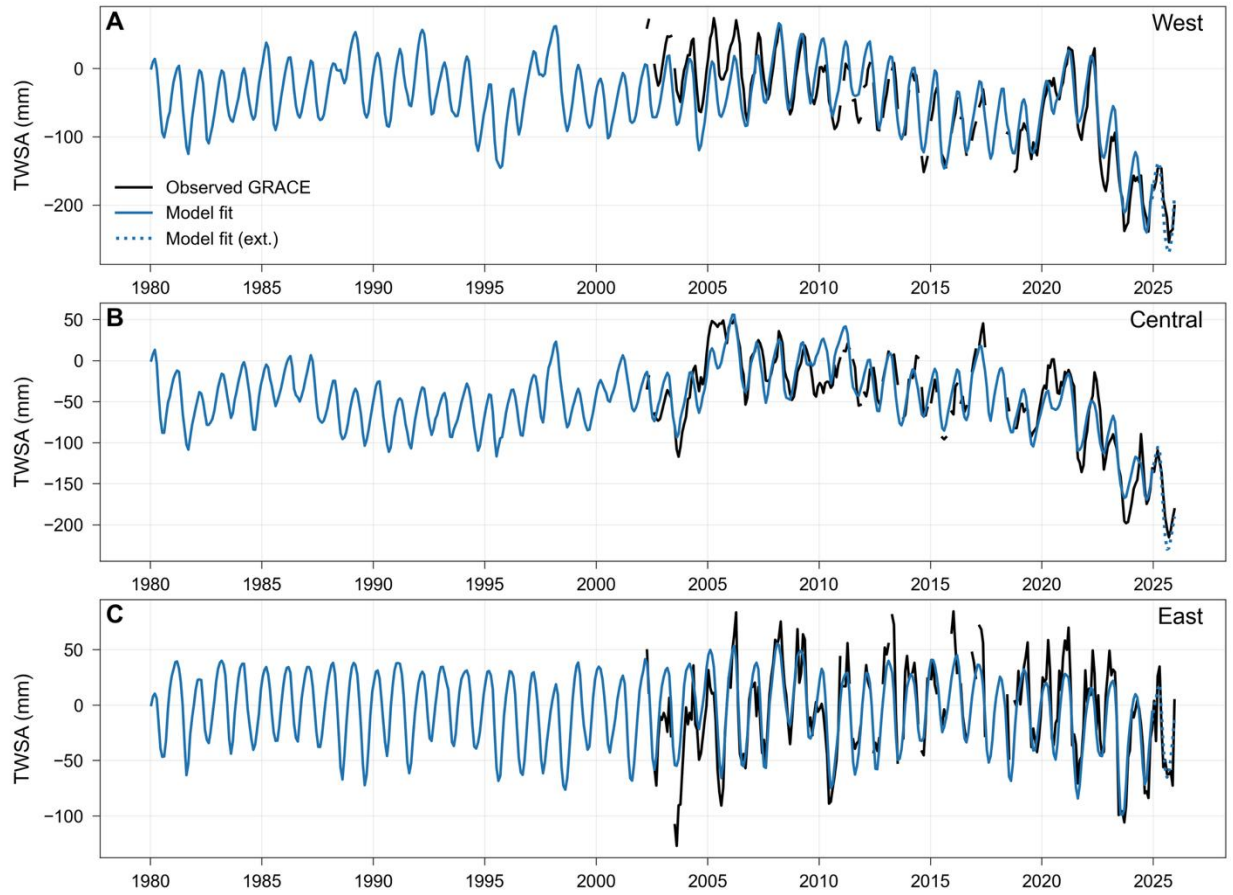


Fig. S2: Observed and modeled terrestrial water storage anomalies (TWSA) for three regions in boreal North America, 1980-2024. Black lines show GRACE satellite observations (2002-2024), and blue lines show model simulations based on a linear model using GPCP precipitation, GLEAM evapotranspiration and a runoff term. Model parameters were calibrated to minimize RMSE during the GRACE observation period. Panels show (a) West, (b) Central, and (c) East regions.

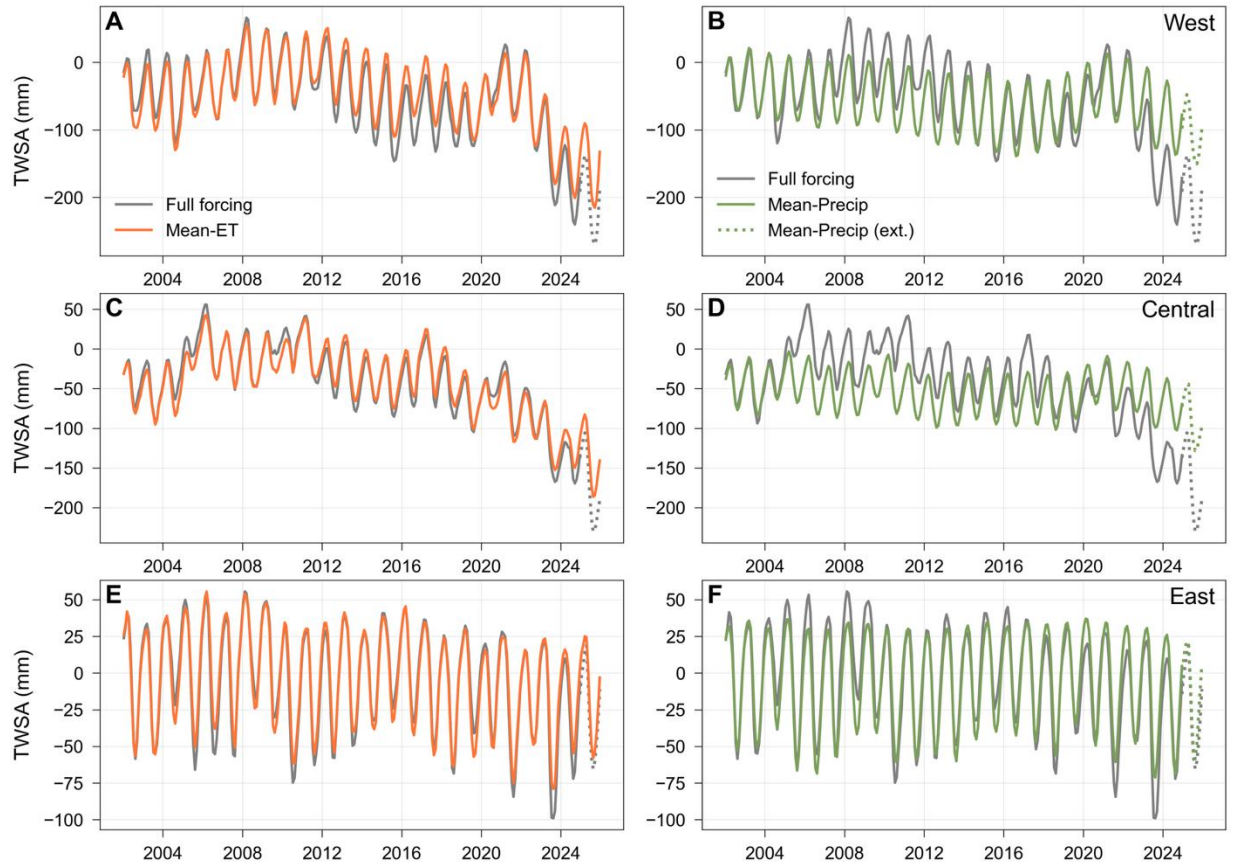


Fig. S3: Sensitivity of modeled terrestrial water storage anomaly (TWSA) to variability in evapotranspiration and precipitation during the GRACE observation period (2002-2024).

Left panels show simulations with evapotranspiration replaced by monthly climatology (orange) compared to the original model from fig. S2 (gray). Right panels show simulations with precipitation replaced by monthly climatology (green) compared to original model (gray). Climatologies are computed as 45-year monthly means (1980-2024). Panels show (A, B) West, (C, D) Central, and (E, F) East regions.

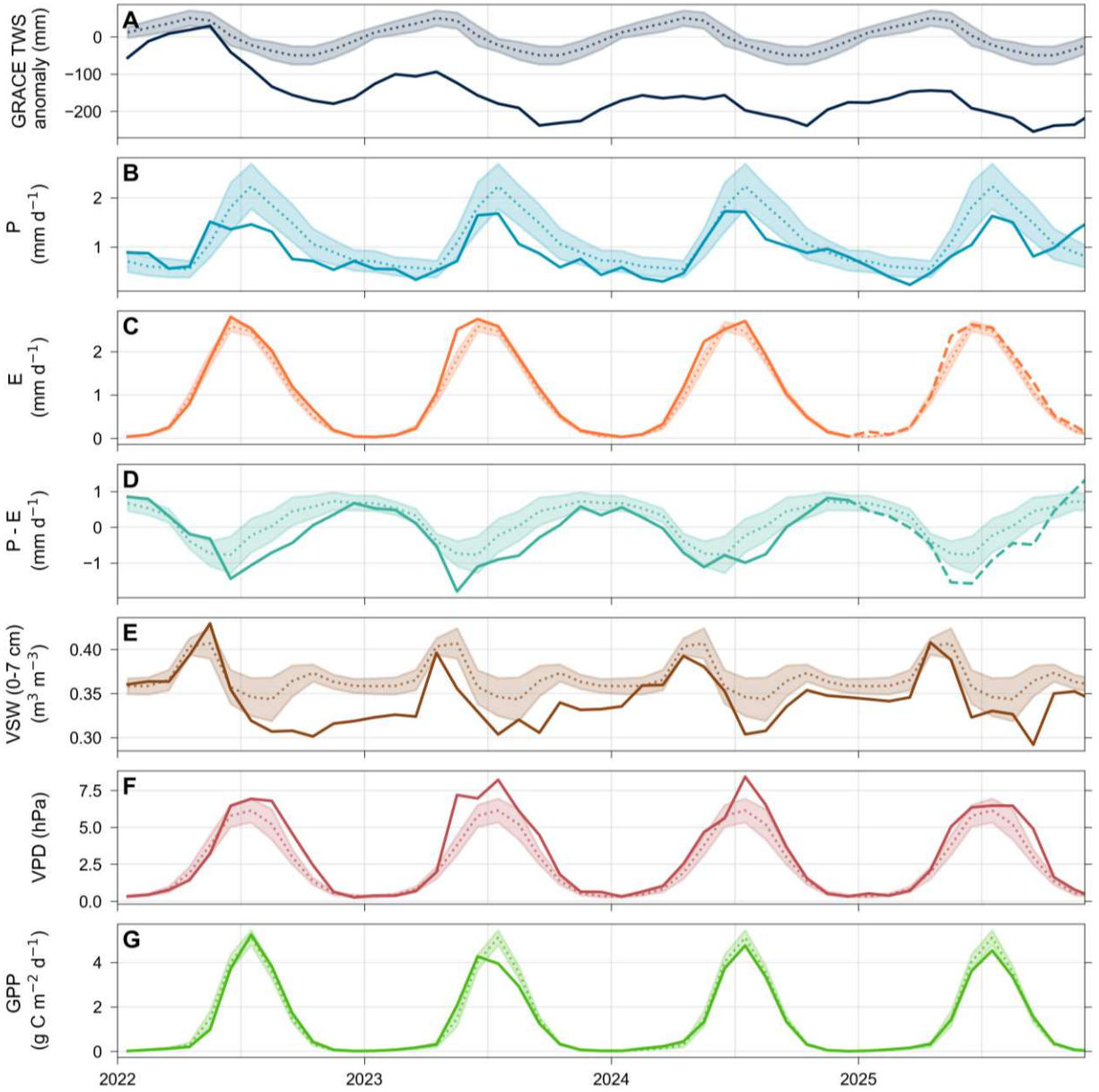


Fig. S4: Monthly hydrometeorological conditions and gross primary productivity (GPP) in western Canada, 2022–2025. Solid lines show monthly observations for (A) Terrestrial water storage (TWS) anomaly, (B) Precipitation (P), (C) Evaporation (E), (D) P minus E, (E) Volumetric soil water (VSW, 0–7 cm depth), (F) Vapor pressure deficit (VPD), and (G) Gross primary productivity (GPP). Dotted lines and shading indicate the climatological mean $\pm$ 1 standard deviation; for A–F the climatology spans 1980–2010 (GRACE from 2002 onwards), and for G it spans 2012–2021. Dashed lines in C and D show E for 2025 estimated from a VPD-based model.

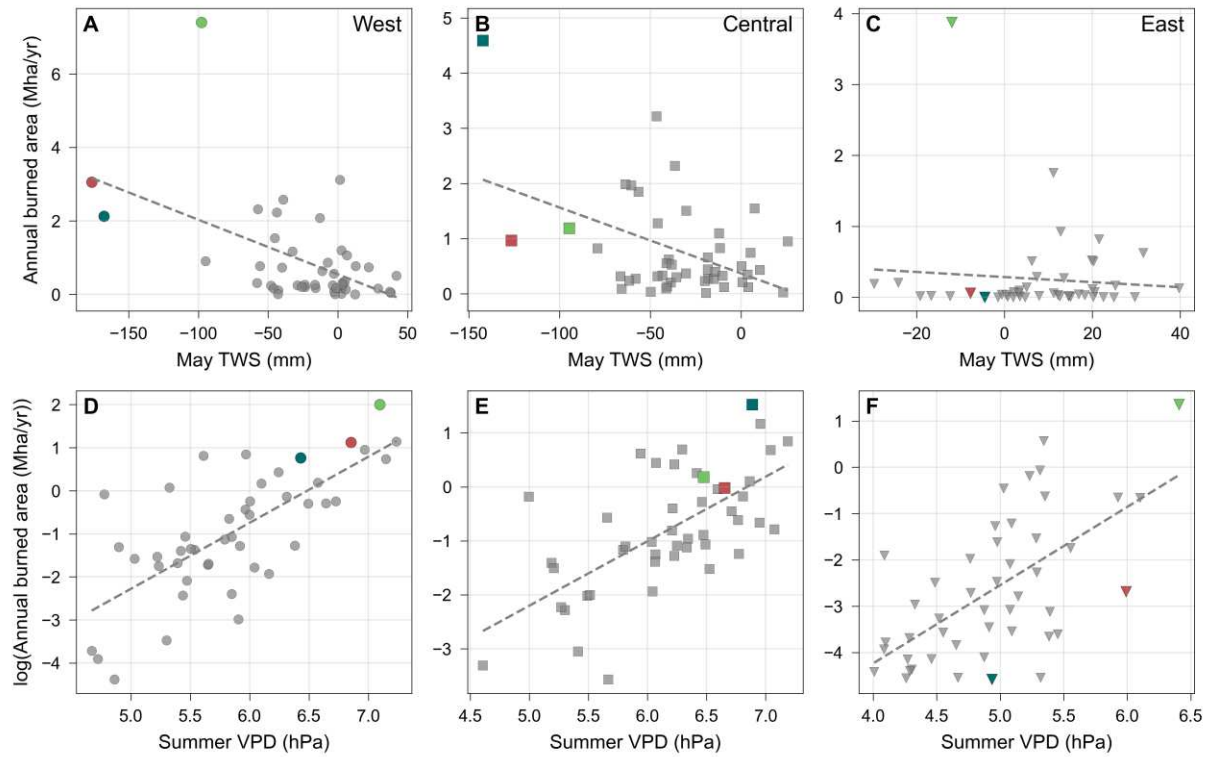


Fig. S5: Relationship between terrestrial water storage anomaly in May and annual burned area from NBAC (A–C) and average summer (June, July and August) vapor pressure deficit and the logarithm of annual burned area (D–F) in the three hotspot regions. Data for 2023, 2024, and 2025 are shown in green, red, and blue, respectively. (A), West, $r = -0.51$, $p < 0.001$; (B) Central, $r = -0.46$, $p = 0.001$; (C) East, $r = -0.08$, $p = 0.58$; (D) West, $r = 0.71$, $p < 0.001$; (E) Central, $r = 0.65$, $p < 0.001$; (F) East, $r = 0.62$, $p < 0.001$.

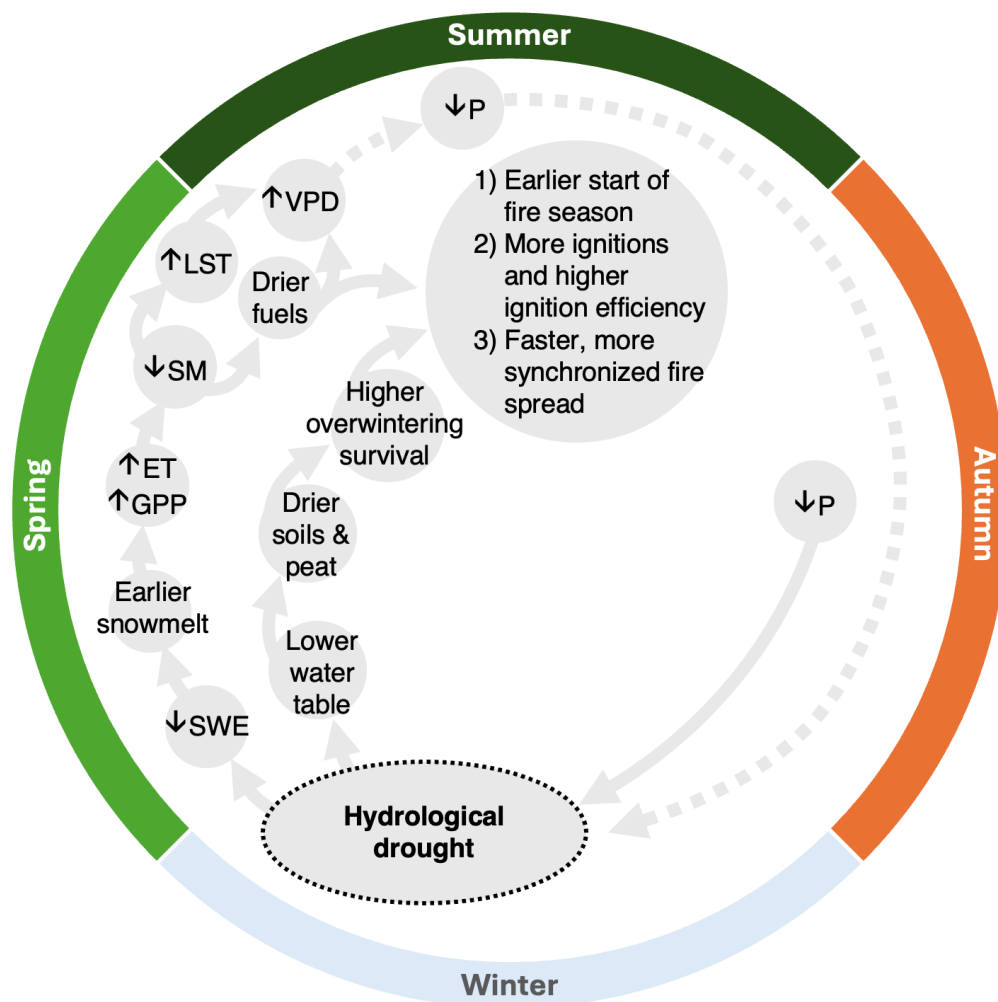


Fig. S6: A conceptual diagram explaining the cascading effects of a precipitation-deficit driven drought on consecutive fire extremes in western boreal North America. P: precipitation, SWE: snow water equivalent, ET: evapotranspiration, GPP: gross primary productivity, LST: land surface temperatures, VPD: vapor pressure deficit.

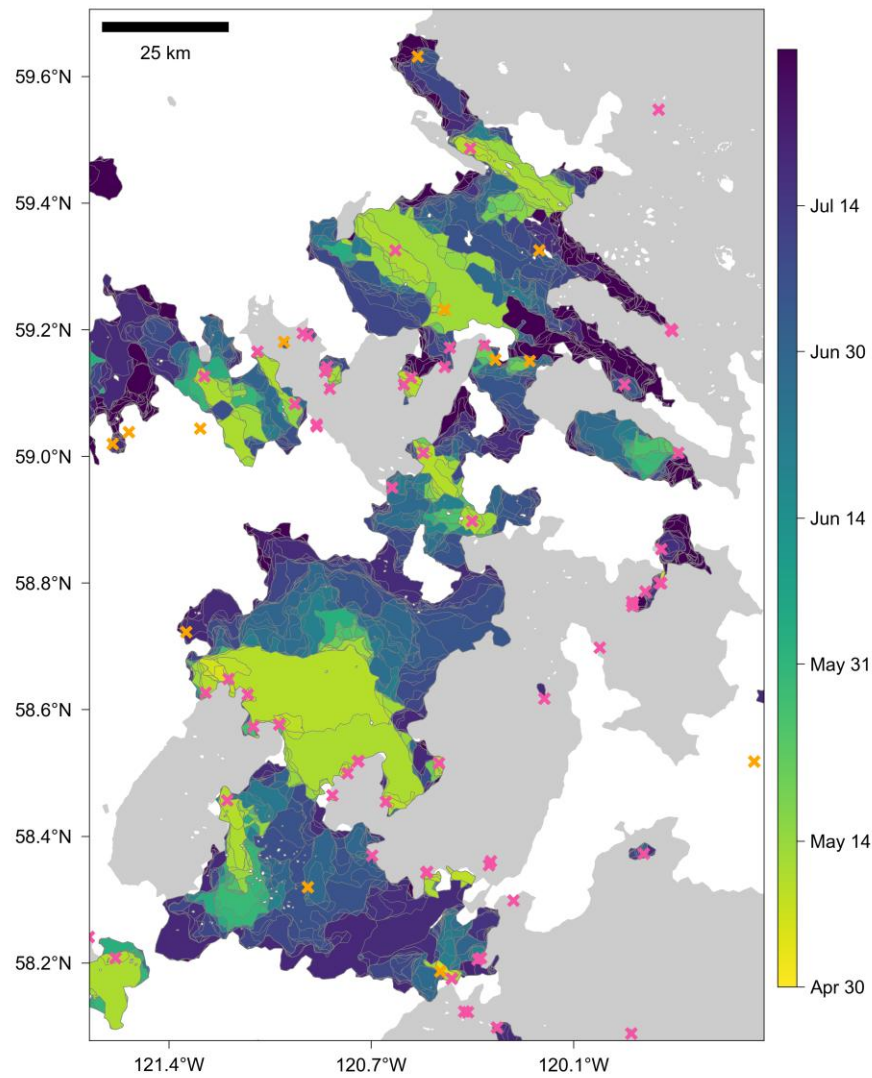


Fig. S7: Detail map of overwintering fire emergence in British Columbia in 2024. Coloring shows progression of burned area in the current year. Gray shows burned area in 2023. Pink markers show overwintering fire starts in 1km buffer zone of previous burned area, orange markers are all other fire starts.

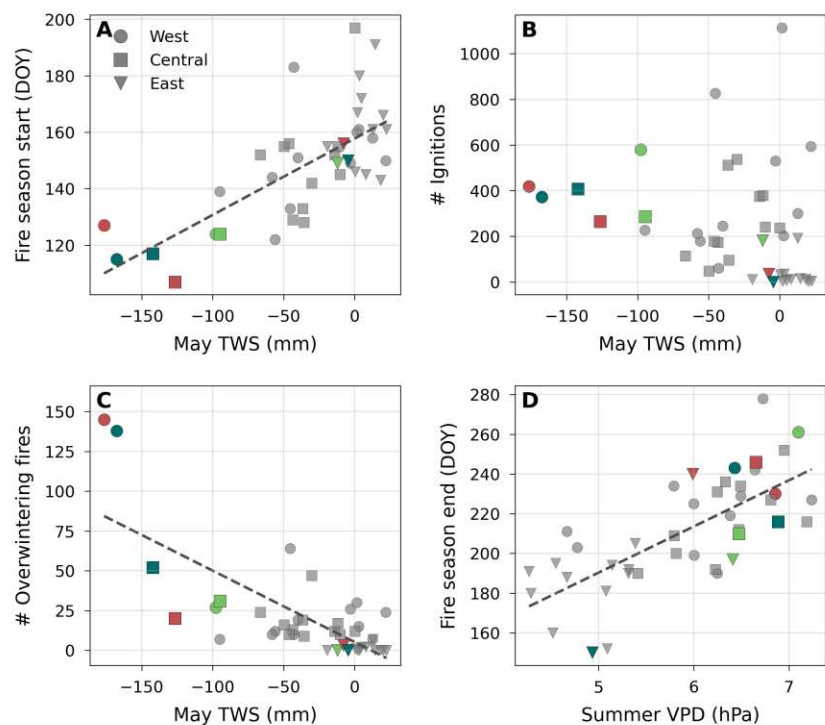


Fig. S8: Scatter plots and regression lines for seasonal correlations between weather variables and fire season characteristics. Data for 2023, 2024, and 2025 are shown in green, red, and blue, respectively. Regression lines are only plotted for significant correlations: **A**, Terrestrial water storage (TWS) in May versus fire season start: $r = 0.70$, $p < 0.001$, **B**, TWS in May versus total number of ignitions: $r = -0.24$, $p = 0.12$, **C**, TWS in May versus number of overwintering fires: $r = -0.74$, $p < 0.001$, **D**, summer (JJA) vapor pressure deficit (VPD) versus fire season end: $r = 0.72$, $p < 0.001$.

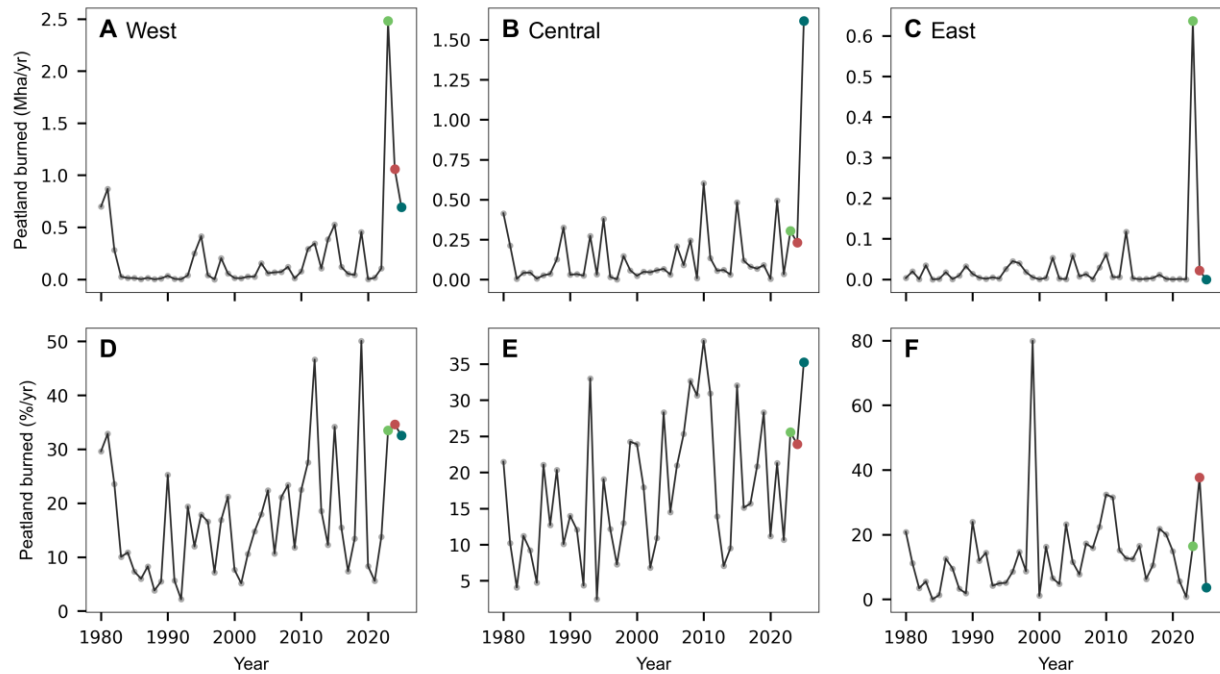


Fig. S9: Annual peatland burned area for the West, Central, and East regions, based on NBAC fire perimeters overlaid with the circumpolar peatland map of Thompson et al. (2019). A–C: Total annual peatland burned area (Mha), D–F: Annual fraction of peatland burned area compared to total burned area. Gray symbols indicate 2012–2022; colored symbols highlight 2023 (green), 2024 (red), and 2025 (teal). Fires in 2023–2025 burned a substantially higher fraction of peatland area compared to 1980–2022 in western (33.5% vs. 16.3%, $z = 1.6$, $p = 0.003$) and central Canada (28.2% vs. 17.0%, $z = 1.2$, $p = 0.02$).

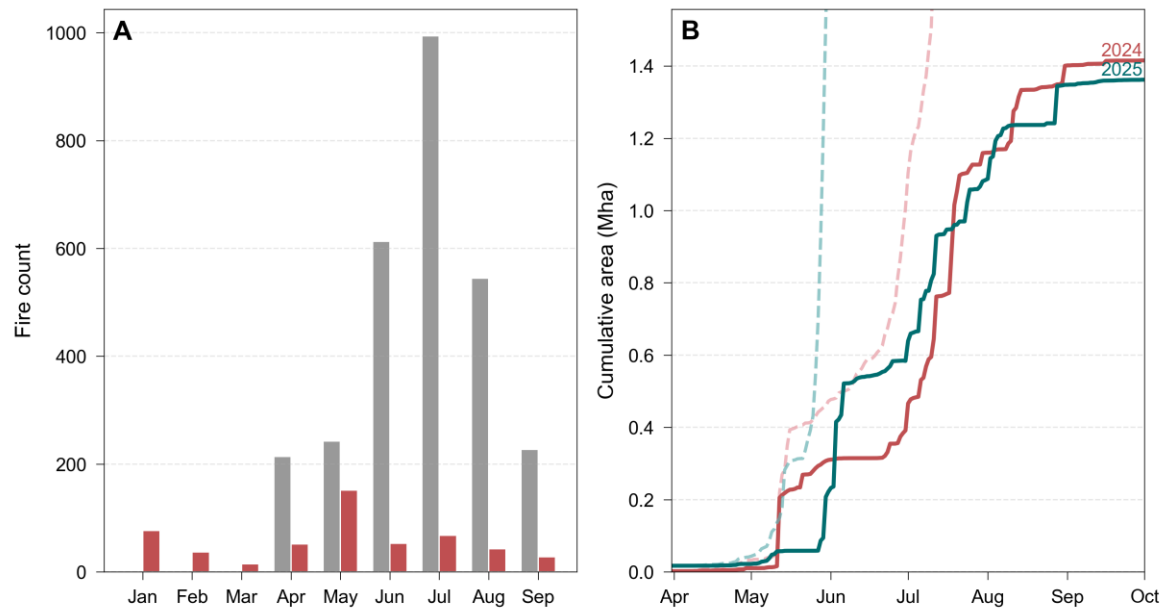


Fig. S10: Timing of overwintering and other fire starts (A), and temporal evolution of overwintering burned area (B) in 2024 and 2025. Red bars in (A) correspond to overwintering fires and grey bars correspond to all other fire starts in boreal North America in 2024–2025. Solid lines in B indicate cumulative burned area from overwintering fires in 2024 and 2025; dashed lines show the cumulative total burned area for reference. Overwintering fires were responsible for 22% of the total burned area in 2024, and 14% of the burned area in 2025.

Table S1: Terrestrial water storage (TWS) anomaly in September of 2023–2025 compared to the climatology of that month (mean and standard deviation). The first three rows ("Obs.") show results based on GRACE observations alone (2002–2021 climatology), while the bottom three rows ("Model") show modelled results using a 1980–2022 baseline. Due to gaps in the GRACE records, the observed climatology does not contain data for 2013 and 2016–2018. For the individual years, absolute values (mm) refer to the recorded TWS anomalies, and z refers to standardized (relative) anomalies (z-scores). The final column shows the mean absolute anomaly across 2023–2025 relative to the climatological mean.

		September Climatology	Sep 2023		Sep 2024		Sep 2025		Mean 2023– 2025 deficit
		mm ($\pm$ SD)	mm	z	mm	z	mm	z	mm
Obs. (2002– 2025)	West	–73 $\pm$ 41	–238	–4.0	–220	–3.6	–255	–4.4	–172
	Central	–50 $\pm$ 43	–196	–3.4	–175	–2.9	–215	–3.8	–136
	East	–44 $\pm$ 23	–106	–2.7	–78	–1.5	–63	–0.8	–23
Model (1980– 2025)	West	–83 $\pm$ 32	–212	–4.0	–240	–4.9	–270	–5.8	–158
	Central	–70 $\pm$ 29	–168	–3.4	–169	–3.4	–229	–5.5	–118
	East	–40 $\pm$ 16	–94	–3.5	–67	–1.7	–60	–1.3	–34

Table S2: Optimized coefficients and measures of fit for modelling regional terrestrial water storage anomalies from GRACE using a linear model. Coefficients are fitted according to equation 1 for precipitation (a), evaporation (b), and a drainage residence time term (τ_D).

	Precipitation coefficient (a)	Evapotranspiration coefficient (b)	Drainage residence time (t_D) [months]	Model R^2	Model RMSE [mm]
West	25.2	30.8	18.1	0.82	32
Central	15.3	19.6	23.7	0.85	23
East	10.9	21.3	4.5	0.71	24

Table S3: Mean terrestrial water storage anomaly (TWSA) deficit during 2023–2025 relative to the 2002–2012 baseline predicted by the three water balance models. The full model uses observed monthly precipitation and evapotranspiration. The P-only model holds ET fixed at its monthly climatological mean, so that the simulated deficit reflects precipitation anomalies alone. The ET-only model holds precipitation fixed at its monthly climatological mean, so that the simulated deficit reflects ET anomalies alone. Relative deficits (%) express each driver's deficit as a fraction of the full model deficit; ranges reflect year-to-year variability across the three individual fire years (2023, 2024, 2025).

	TWSA mean deficit in 2023–2025 (mm)			Fraction of full model deficit (%)	
	Full model	P-only model	ET-only model	P-driven	ET-driven
West	–138	–111	–33	75–77%	23–25%
Central	–117	–104	–19	82–85%	15–18%
East	–29	–18	–10	59–72%	28–41%

Table S4: Model comparison for the entire domain, and individual regions. The model includes either only an exponential term for the summer (JJA) vapor pressure deficit (VPD) in the form: $Burned\ area = a + b \times e^{(c \times VPD)}$ or the same model with an additional term $d * TWS$, with TWS corresponding to the modelled terrestrial water storage anomaly for the month of May. Adding TWS improved model performance for the whole domain, West and Central, but not the East subregion.

Region	Predictor(s)	R ²	Adj. R ²	RMSE	MAE	AIC	BIC
Whole domain	VPD	0.43	0.41	0.77	0.45	-67.6	-58.8
	VPD + TWS	0.51	0.50	0.70	0.43	-88.8	-77.1
West	VPD	0.55	0.51	0.87	0.52	-7.3	-1.8
	VPD + TWS	0.69	0.66	0.72	0.45	-22.8	-15.5
Central	VPD	0.28	0.23	0.75	0.50	-20.0	-14.5
	VPD + TWS	0.43	0.37	0.67	0.49	-28.3	-21.0
East	VPD	0.75	0.73	0.32	0.19	-99.7	-94.2
	VPD + TWS	0.75	0.73	0.31	0.19	-99.1	-91.8

Table S5: Correlations between annual burned area and modelled terrestrial water storage anomalies in January, February, March, April and May.

	Jan		Feb		Mar		Apr		May	
	R	<i>p</i>	R	<i>p</i>	R	<i>p</i>	R	<i>p</i>	R	<i>p</i>
Whole domain	-0.40	<i>< 0.001</i>	-0.39	<i>< 0.001</i>	-0.39	<i>< 0.001</i>	-0.41	<i>< 0.001</i>	-0.50	<i>< 0.001</i>
West	-0.40	<i>0.006</i>	-0.40	<i>0.005</i>	-0.41	<i>0.005</i>	-0.42	<i>0.004</i>	-0.51	<i>< 0.001</i>
Central	-0.26	<i>0.08</i>	-0.27	<i>0.07</i>	-0.28	<i>0.06</i>	-0.32	<i>0.02</i>	-0.46	<i>0.001</i>
East	-0.03	<i>0.83</i>	-0.05	<i>0.73</i>	-0.05	<i>0.72</i>	-0.02	<i>0.88</i>	-0.08	<i>0.58</i>

Table S6: Contributions of overwintering fires and newly started fires to regional total burned area and carbon emissions for 2024 and 2025 in the western, central and eastern Canadian subregion.

Region	Burned area year	Ignition source year	# Fires	Burned area (Mha/y)	Burned area (Annual fraction)	Emissions (Tg C/y)	Emissions (Annual fraction)
West	2024	2024	274	2.87	0.73	147.7	0.76
		2023	139	1.08	0.27	46.8	0.24
		2022	6	0.00	0.00	0.0	0.00
	2025	2025	234	2.17	0.80	73.6	0.82
		2024	69	0.38	0.14	11.4	0.13
		2023	69	0.14	0.05	4.6	0.05
Central	2024	2024	245	1.22	0.99	57.3	0.99
		2023	16	0.02	0.01	0.7	0.01
		2022	4	0.00	0.00	0.0	0.00
	2025	2025	356	5.63	0.91	183.0	0.91
		2024	34	0.40	0.06	14.9	0.07
		2023	18	0.13	0.02	3.7	0.02
East	2024	2024	33	0.05	0.99	0.7	0.99
		2023	3	0.00	0.01	0.0	0.01
		2022	0	0.00	0.00	0.0	0.00
	2025	2025	1	0.00	1.00	0.0	1.00
		2024	0	0.00	0.00	0.0	0.00
		2023	0	0.00	0.00	0.0	0.00