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Wildfire drives widespread and decadal change in boreal lake color

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Wildfire drives widespread and decadal change in boreal lake color

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Abstract

Wildfire regimes are intensifying across boreal Canada, with cascading impacts on the region's abundant lakes, yet the long-term consequences for lake color and water quality remain poorly constrained at regional scales. Here, we use harmonized Landsat time series and a causal Difference-in-Differences analysis to quantify fire-driven lake color change and its controls across western boreal Canada. Across 93 fires affecting ~14,700 burned lakes during 2005–2015, we found pervasive, persistent fire-driven increases in lakes' red-band surface reflectance (SR_{Red}), a proxy for suspended sediment concentration and turbidity, compared to unburned lakes. This increase emerged in the first post-fire summer (median 13%; interquartile range 5–21%) and grew to 17% (7–30%) ten years after fire, with lakes in 45% of fires showing no recovery within the decade. Increases were larger and lasted longer in clearer and smaller lakes and after more severe burns. These findings demonstrate wildfires as an important driver of long-term boreal lake color dynamics, posing challenges to aquatic habitat and water resource management as fire activity increases.

Introduction

Climate change is rapidly intensifying wildfire regimes across boreal Canada, with projected increases in both fire severity and annual burned area[1–3]. The impacts of these fires cascade beyond terrestrial ecosystems into streams and lakes, altering hydrology, biogeochemistry, and aquatic habitat[4–7]. The western Canadian boreal forest, a hotspot of intensifying fire activity[2], contains over 1.5 million inland lakes that play a critical role in supporting aquatic habitats, carbon cycling, and water security of Indigenous and downstream communities[8–10]. However, while the terrestrial impacts of fires are extensively researched in boreal forests, their impacts on lakes remain poorly constrained, especially at regional scales and over long periods[6,11].

Wildfire degrades lake water quality primarily by mobilizing sediment from burned catchments. Combustion of vegetation and organic soil layers removes stabilizing cover, increasing surface runoff and erosion that deliver suspended sediments, ash, and organic particles to receiving waters[11–14]. Reduced evapotranspiration, soil water absorption, and canopy rainfall interception in burned catchments further amplify these effects, with post-fire surface runoff increasing up to tenfold[15,16]. In permafrost terrain, fire-promoted permafrost thaw can further sustain sediment supply through thaw-driven mass wasting such as retrogressive thaw slumps[17,18]. The resulting increases in suspended sediment and turbidity degrade water quality, posing challenges to the aquatic biota and northern communities that rely on these lakes for drinking, subsistence, and recreation[9,11,19]. Burn severity, catchment burned ratio, watershed hydrology, and lake

characteristics (such as size, depth, and trophic status) have all been identified as key factors affecting lake responses to fire in various ecosystems[11,15,20–22].

Despite this mechanistic understanding, the prevalence and persistence of fire-driven changes in lake water quality remain largely unknown. Most evidence for post-fire sediment increases comes from streams and rivers, where effects typically last from months to 2–3 years, whereas lake studies have focused primarily on other constituents than sediment or turbidity[14,23–25]. In-situ studies among boreal lakes have reported inconsistent results, ranging from increases in light attenuation, nutrients, and dissolved organic carbon (DOC) to no detectable response in lake geochemistry within 1–3 years of fire[26–29]. These inconsistencies likely reflect the small spatial coverage and varied designs of individual studies, hindering generalizable conclusions across broad scales[11,14]. Moreover, post-fire monitoring rarely exceeds five years after fire[11,15], precluding assessment of full recovery trajectories. In boreal Canada, multi-decadal lake record from sediment cores showed elevated sedimentation rates lasting for more than two decades after a fire[30], suggesting that fire legacies in boreal lakes may far outlast current monitoring. Consequently, it remains unclear how prevalent post-fire changes in water quality are across boreal lakes, and how long they persist.

Here, we quantify the long-term causal effects of wildfire on lake color across western boreal Canada using satellite remote sensing, which enables consistent monitoring across large spatial and temporal extents[31]. Using Landsat time series and Difference-in-Differences (DiD) regression, we quantified the impacts of 93 wildfires (2005–2015) on 14,759 burned lakes. Lake color was quantified as red-band surface reflectance (SR_{Red}, ~660 nm), a robust proxy for relative changes in suspended sediment and turbidity[32–35]. We find that wildfire increased lake color (SR_{Red}) from the first post-fire summer throughout the ten-year post-fire window, far beyond the few years captured by most previous studies.

Results

Heterogeneous fires and landscape

The burned lakes spanned a wide range of lake and fire characteristics, including lake size and baseline color, number of lakes per fire, burn severity, and burned area (Fig. 1). The number of burned lakes per fire averaged 159 but varied widely from 30 to 1,646 (Fig. 1d). This landscape is dominated by small lakes[8], with 40% of all burned lakes smaller than 0.1 km^2. The number of fires per year showed an overall upward trend and peaked in 2014 (Fig. 1a). The average burn severity (measured by mean difference in normalized burn ratio (dNBR) of each fire) and burned area of these fires were 0.53 and 639 km^2, respectively (Fig. 1b and c).

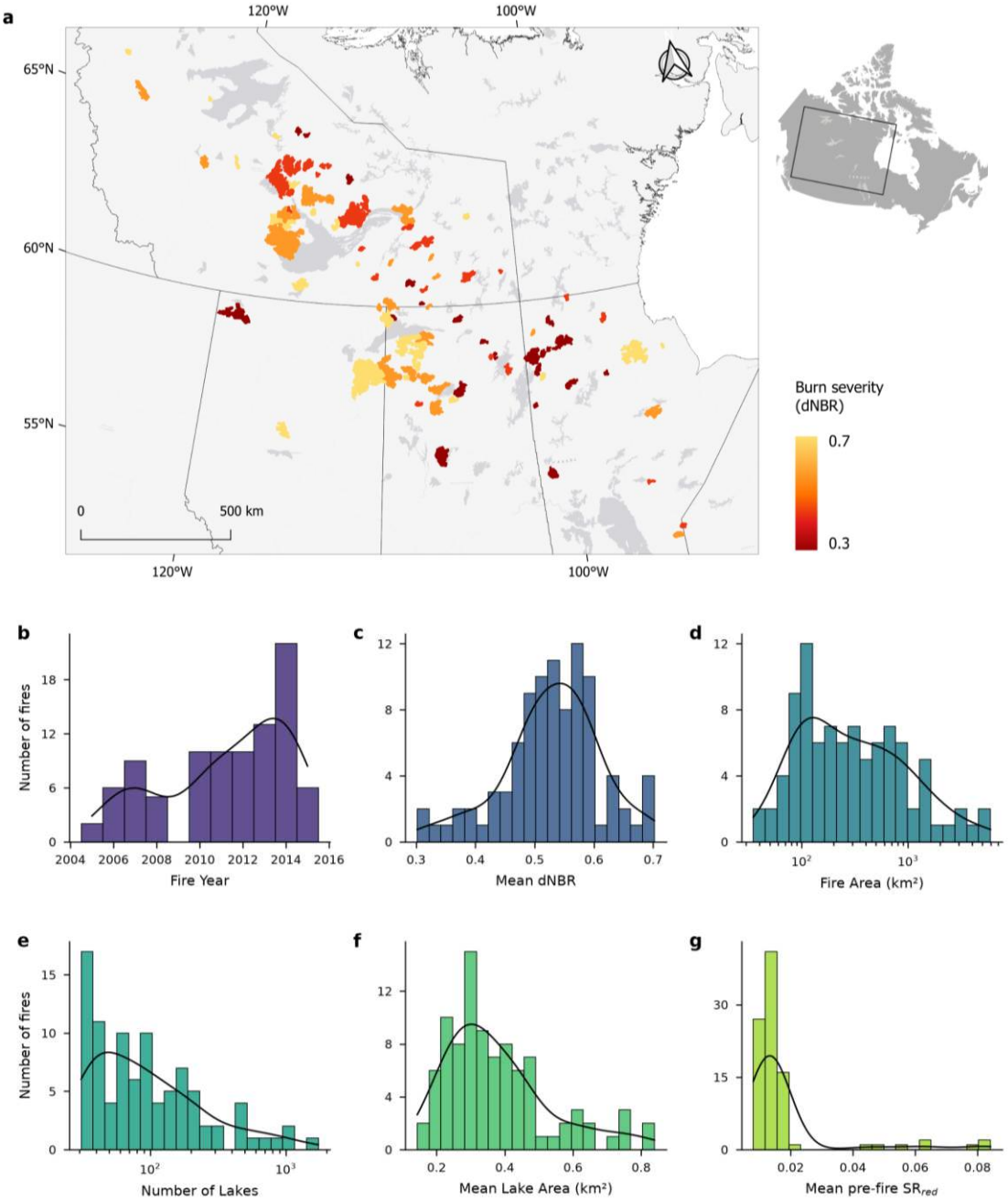


Fig. 1. Map of 93 analyzed wildfires (2005–2015) across western boreal Canada, colored by burn severity (mean dNBR) (a) and distributions of fire and lake characteristics (b–g). Fire area (c) and number of burned lakes per fire (d) were log-transformed on the x-axis.

Pervasive and decadal fire-driven change in lake color

We observed a pervasive fire-driven increase in lake SR_{Red} across western boreal Canada. We quantified this effect as δ_τ per fire per year, the DiD estimate of fire-driven change in SR_{Red} in the τ-th year after fire, expressed as percentage change from pre-fire SR_{Red} (Methods). The median and interquartile range (IQR) of δ_τ across all fires was 13% (5–21%) in the first year post-fire, and

remained positive in every subsequent year (Fig. 2), indicating a consistent positive impact of fire on reflectivity across physiographic and fire variations. The median and IQR of δ_τ fluctuated around zero for all $\tau < 0$, supporting the DiD parallel-trends assumption of similar color trajectories of burned and control lakes aside from fire.

This positive impact of fire disturbance on lake SR_{Red} did not fade over the decade we observed (Fig. 1a). The median δ_τ increased monotonically over the ten-year window (Mann-Kendall τ_{MK} = 0.56, $p < 0.05$) and reached 17% (IQR = 7–30%) by $\tau = 10$, a higher value than the initial response of 13% (Fig. 2). In addition, extending the post-fire regression window to 15 years for the 22 earliest fires (2005–2009) confirmed that the elevated δ_τ was sustained beyond a decade (Fig. S1). For this subset of early fires, the median δ_τ remained positive for all 15 years and was generally higher through years 10–14 (medians = 15–23%) than in the first few post-fire years, with no return toward baseline over this period.

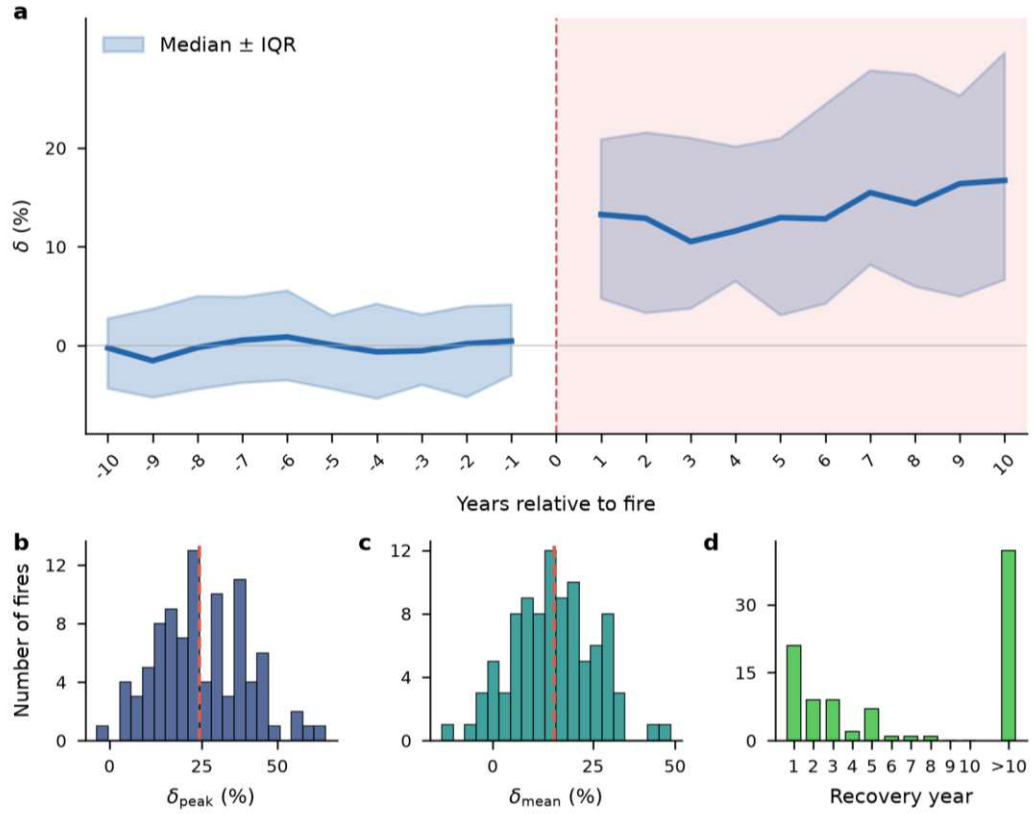


Fig. 2. Annual time series of post-fire δ_τ (plotted as % change of pre-fire SR_{Red}) (a), representing annual fire-driven percentage change in lake SR_{Red} of 93 fires (2005–2015) across western boreal Canada (blue line = median, shading = interquartile range (IQR)), accompanied by the distributions of post-fire δ_{peak} (%), δ_{mean} (%), and recovery year (b–d).

Across the 93 fires, the median peak (δ_{peak}) and mean (δ_{mean}) of δ_τ within the first post-fire decade were 24% (95% confidence interval (CI) = 22–29%) and 15% (CI = 12–18%), respectively (Fig. 2b and c), and neither metric was significantly associated with the fire's year or burned area ($p > 0.05$). Only one fire caused a sustained decrease in lake color throughout the 10-year window,

with a δ_{peak} of −3% and a δ_{mean} of −11%.

Nearly half of the fires had not recovered within a decade. Defining the recovery year as the number of years until the fire effect δ_{τ} returned to within ±10% of its pre-fire baseline (see Methods), we found that lakes of 21 fires recovered in one year post-fire. Lakes within 30 additional fire scars recovered later in the decade, while those of the remaining 42 fires (45% of all fires, CI = 35–56%) showed no recovery ten years after burning (Fig. 2d).

Baseline lake color and burn severity as primary controls on lake responses to fire

The magnitude of fire-driven change in lake SR_{Red} varied with physiographic and fire characteristics, governed primarily by pre-fire lake color and burn severity.

The fires spanned five ecoregions of Taiga Plains, Taiga Shield, Boreal Plains, Boreal Shield, and Hudson Plains[36], exhibiting strong regional gradients in permafrost extent, surficial geology, and vegetation cover. As the landscape transitions from boreal forest in the south to tundra in the north, the probability of permafrost increases and vegetation cover (measured by leaf area index (LAI)) decreases, with a moderate negative association between them (r = −0.56). Geologically, the Plains ecozones to the west are characterized by thick glacial and peat deposits, in contrast to the thin soils over bedrock in the Shield, contributing to different trophic states and optical properties of lakes[26,36,37]. To identify which of these properties controlled the lake response, we combined two analyses: comparison of the post-fire δ_{τ} trajectories of lakes stratified by each setting (Fig. 3), and a regression of δ_{peak} and δ_{mean} on each quantifiable control across fires (Fig. 4).

Fires and associated burned lakes stratified by burn severity showed the largest separation in their post-fire δ_{τ} trajectories (Fig. 3a). Based on the average dNBR of the burned area, the 93 fires were categorized as 35 moderate- and 58 high-severity fires, with no low-severity fire[38]. δ_{τ} of high-severity fires exceeded that of moderate fires in every post-fire year, and the gap continued to widen over the decade to a median of 22% versus 13% by year 10. The permafrost contrast was smaller but similarly consistent in direction (Fig. 3b). Burned lakes in areas of high permafrost probability exerted a higher fire-driven increase in SR_{Red} compared to areas of low-to-moderate permafrost probability for every post-fire year, but such distinction was not observed between high and low LAI areas (Fig. S2).

The geological and ecological contrasts were less distinct. While lakes in the Taiga and Shield ecozones generally had stronger fire-driven increases in SR_{Red} compared to those of the Boreal and Plain ecozones, such differences were less consistent throughout the post-fire decade (Fig. 3c and d).

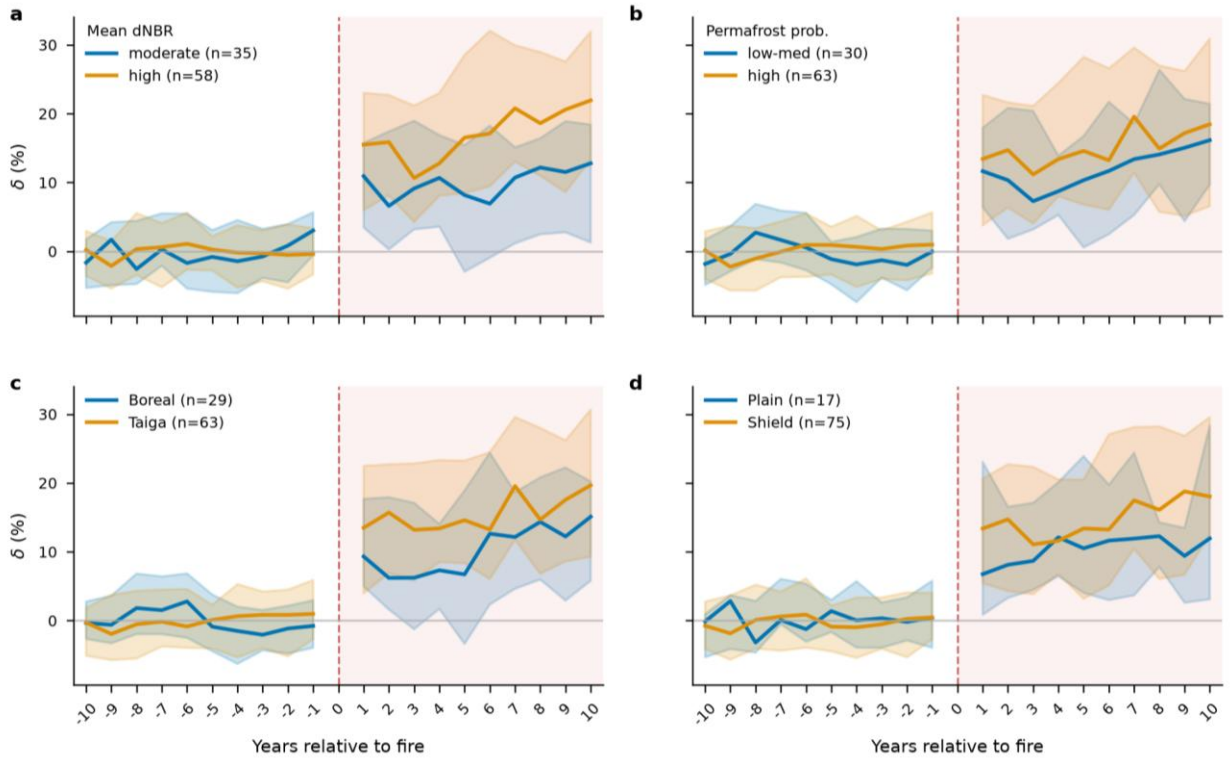


Fig. 3. Annual time series of post-fire δ_τ (%), stratified by (a) burn severity (mean dNBR), (b) permafrost probability, and (c) the ecological (Boreal or Taiga) and (d) geological (Plain or Shield) settings of each fire.

Based on the linear regression between fire-driven lake color change (δ_{peak} and δ_{mean}) and each control, pre-fire baseline lake color was identified as the most important control, with lower pre-fire SR_{Red} associated with both higher δ_{peak} and δ_{mean} (Pearson r = −0.51 and 0.49, p < 0.01, Fig. 4). Nine fires clustered in the Taiga Plains ecozone had substantially higher pre-fire lake SR_{Red} (0.04–0.08) and followed a distinct regression relationship, which were thus removed from this regression to avoid skew (Fig. S3).

Burn severity (mean dNBR) was the second-strongest control and was positively associated with both δ_{peak} and δ_{mean} (r = 0.44 and 0.46, p < 0.01, Fig. 4), consistent with the clear separation in δ_τ trajectories among burn severities (Fig. 3a). In addition, lakes affected by high-severity burns tended to recover more slowly than those by moderate-severity fires. By year 10, lakes within 53% of high-severity fires remained unrecovered compared to 31% of moderate-severity fires (Kaplan–Meier, p < 0.05). By contrast, neither permafrost probability nor LAI appeared to be a statistically significant control (p ≥ 0.1) on the magnitude or persistence of lake responses to fire, albeit the slightly higher median of δ_τ for fires in areas of high permafrost probability (Fig. 3b).

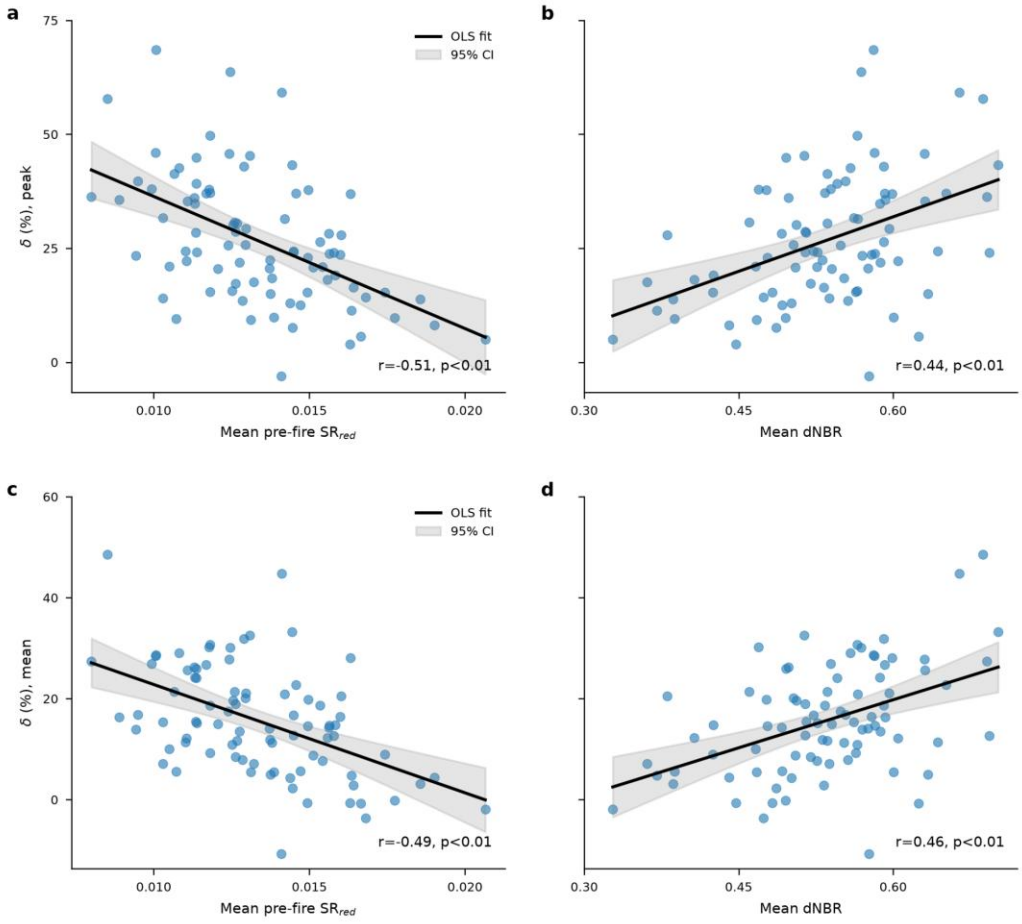


Fig. 4. Ordinary Least Squares (OLS) regression and 95% confidence interval (CI) between fire-induced lake SR_{Red} change (δ_{peak} and δ_{mean}, %) and the two strongest controls: baseline lake color (mean pre-fire SR_{Red}, n = 84, outliers removed) (a and c) and fire severity (mean dNBR, n = 93) (b and d).

Small lakes respond more strongly to fire

Small lakes responded more strongly to the same fire than large ones did (Fig. 5b). Dividing burned lakes into the smallest and largest area tertiles (≤ 0.08 km² and > 0.21 km², respectively) and re-running the DiD regression separately for each group, we found that small lakes consistently experienced a greater proportional increase in SR_{Red} than large lakes, while both groups followed similar pre-fire parallel trends (Fig. 5). This separation emerged in the first post-fire year and widened thereafter, reaching a median δ_τ of 22% for small lakes and 12% for large lakes by year 10. Correspondingly, both median δ_{peak} and median δ_{mean} were statistically higher in small lakes than in large lakes across all fires (one-tailed Wilcoxon signed-rank test; $p < 0.01$) (Fig. 5b).

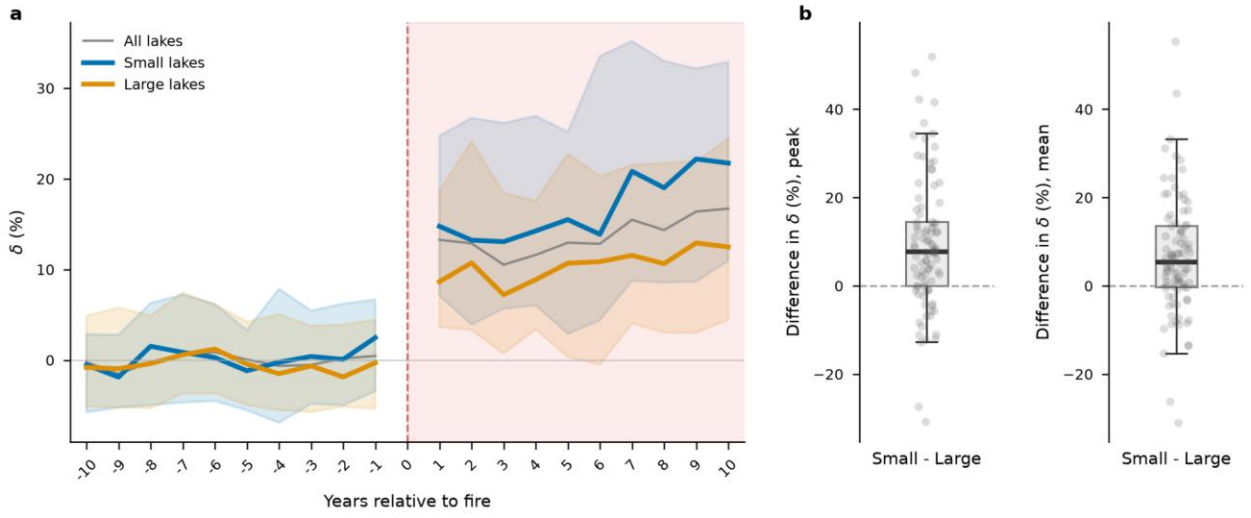


Fig. 5. Stronger fire-driven lake color change in small lakes—(a) Annual time series of post-fire δ_T (plotted as %) for small lakes (blue), large lakes (orange), and the full sample (grey) (line = median, shaded area = IQR); (b) Distribution across fires of the per-fire difference (small lakes − large lakes) in δ_{peak} and δ_{mean} (boxes = median and IQR, whiskers = range, points = individual fires).

Discussion

Our results indicate a pervasive fire-driven increase in lake SR_{Red} across western boreal Canada despite physiographic and fire variations. This elevated lake SR_{Red} is attributed to fire-driven increases in suspended sediment input and lake turbidity, widely reported in fire-disturbed streams and lakes due to increased surface runoff and bank erosion after fire[13–15,20]. These changes often coincide with increased nutrient delivery, suggesting coupled biogeochemical responses to fire[15].

Wildfire impacts on lake color persisted for at least a decade, with lakes in nearly half of the fires (42 of 93) showing no recovery after ten years, far exceeding the commonly reported 1–3 years of increased suspended sediment or turbidity and altered biogeochemistry[15,20]. However, these durations largely reflect limited monitoring windows instead of actual recovery. Our results instead agree with longer-term sediment-core studies, such as the four subarctic lakes in Yukon that showed increasing sedimentation rates for over two decades post-fire[30]. Such persistence likely reflects slow terrestrial ecosystem recovery in boreal forests[15,30], which can take decades due to low temperatures, short growing seasons, and limited nutrient availability compared to temperate ecosystems[20,24,30].

Severe burns further amplify and prolong fire impacts, consistent with previous findings that identified burn severity as a primary control on post-fire water quality degradation and recovery periods[14,15,39]. In boreal Canada, the dominance of needleleaf trees often leads to high-severity burns[40,41] that can consume the insulating organic soil layer, increasing the risk of regeneration failure and multi-decadal permafrost thaw[6,42]. Together, slow recovery and high burn severity make boreal lakes particularly vulnerable to prolonged fire impacts, and this vulnerability will likely increase as fires become more severe[43,44].

Lakes' baseline color and area also mediate their response to fire. While turbid lakes with higher baseline SR_{Red} may receive fire-induced sediment inputs comparable to those of clear lakes, this influx represents a smaller percentage change, thus appearing as a more resilient response. This is consistent with the stronger response of Shield lakes, which are typically oligotrophic, clearer, and more influenced by mineral-soil inputs than Plains lakes[11,27,45]. Similarly, the higher catchment-to-lake-area ratio and lower water volume of smaller lakes may amplify the relative turbidity increase from fire-mobilized sediments, contributing to their higher sensitivity than larger lakes[15,23,29].

Our fire-level causal analysis isolated the fire-driven signal and identified important controls across broad scales, but precluded the investigation of lake-level controls identified by previous studies, such as hydrological connectivity, catchment size, and watershed burn ratio[11,20,21]. Further regional lake-level analyses could address these factors to complement our results and enhance the understanding of fire-lake interactions. Finally, as a proxy for suspended sediment, SR_{Red} can be influenced by other optically active constituents such as colored dissolved organic matter (CDOM) and phytoplankton. However, post-fire responses of these constituents in boreal lakes have been inconsistent[10,46], making them an unlikely explanation for the pervasive, decade-long increase we observed, although future in-situ measurements would help confirm the sediment signal.

Current wildfire and water management frameworks in boreal Canada largely overlook fire-lake interactions, with the long legacies of fire on water quality being poorly understood. Yet persistent increases in lake color and turbidity matter both for northern communities that rely on traditional water sources[9] and aquatic biota sensitive to changes in water quality[19,47]. Our results show that these impacts can last more than a decade and intensify with burn severity, highlighting the potential of severity-reducing practices, such as Indigenous-led fire stewardship[48]. As fire activity intensifies across landscapes where in-situ data are scarce, our framework offers a scalable path toward understanding and monitoring these impacts.

Methods

Fire and lake selection

Our study covered wildfires across the boreal forest of western Canada, including the provinces and territories of Yukon, Northwest Territories, Nunavut, British Columbia, Alberta, Saskatchewan, and Manitoba. We analyzed fires that occurred between 2005 and 2015, a window chosen to provide sufficient Landsat records for both the pre-fire parallel-trends test (≥ 5 years) and the post-fire DiD trajectory (≥ 10 years). The perimeter of each fire, along with burned area and fire date, was retrieved from the National Burned Area Composite (NBAC)[49].

For each fire, we identified burned and control lakes with a surface area of 0.04–10 km^2 using the WBD–NAHL dataset[8], which delineates surface water bodies across tundra and boreal North America from 10 m Sentinel-2 imagery. We defined burned lakes as lakes completely within the fire perimeter and selected nearby control lakes from a dynamic ring buffer around the fire perimeter. The outer radius of the buffer was set to the fire's equivalent circular radius, clamped between 10 and 30 km; the inner radius was set to 1 km beyond the perimeter, excluding near-

perimeter lakes susceptible to direct inputs from burnt-shoreline erosion and fire-proximal ash deposition[50].

Landsat reflectance time series construction

We used Collection-2 Level-2 Landsat 7 (ETM+) and Landsat 8 (OLI) surface reflectance products[51,52] and applied tailored cross-calibration before reflectance retrieval[53]. While Landsat 7 and 8 products offer extensive temporal coverage, cross-sensor biases have been identified in their surface reflectance observations, stemming from differences in their spectral response, radiometric fidelity, and atmospheric correction algorithms[34,54]. These biases were shown to induce spurious reflectance changes in high-latitude lakes and require accounting for using tailored cross-calibration[53]. Following the same calibration procedures as Chang et al.[53], we extracted paired lake-level observations of red-band surface reflectance (SR_{Red}) from overlapping Landsat 7 and 8 scenes in ten 100 km^2 tiles spanning western boreal Canada. We then estimated a calibration function from all paired observations using orthogonal distance (Deming) regression, and applied it to all Landsat-8 reflectance observations[53,55].

We constructed lake-level annual summer composites of SR_{Red} from the harmonized Landsat 7–8 time series. For each lake, we selected all overpassing scenes from July and August (ice-free months) and removed invalid pixels that were:

1) flagged by the Quality Assurance band for cloud, cloud shadow, aerosol, radiometric saturation, or Landsat-7 scan-line errors [51,52];
2) Above 0.03 in the shortwave-infrared (SWIR) band or above 0.15 in the near-infrared (NIR) band, to eliminate floating vegetation, cirrus clouds, and/or ice cover[53]; or
3) within the littoral zone, identified by a 60 m inward buffer (equivalent to two Landsat pixels) in each lake polygon to remove interference from land-water mixed pixels and adjacency effects.

We computed the lake-wise mean of retained pixels within each scene, then took the median across all July–August scenes to yield the annual summer SR_{Red} per lake[56,57]. Finally, we discarded lakes that had fewer than three valid, non-littoral Landsat pixels or were drained during the study period.

Additional fire- and lake-filtering was applied to ensure the validity of the Difference-in-Differences (DiD) analysis. First, to prevent stacking effects of repeated burns, we removed any burned or control lake that had been affected by another fire within ±20 years of the focal fire. We then discarded a fire if it was constrained by:

1) spatial bias due to repeated burns, where more than 80% of either the burned or the control lakes initially identified for the fire had been affected by another fire within the ±10-year DiD regression window, leaving a spatially biased collection of lake samples; or
2) insufficient sample size, where fewer than 30 burned or control lakes remained, to prevent the outlier effects of a small sample size.

All retained SR_{Red} values were then transformed by natural logarithm before the DiD analysis. As fires differ in their pre-fire SR_{Red} baseline, expressing effects as proportional changes on a log scale facilitated valid cross-fire comparisons[58]. We additionally performed the same DiD analysis

using the raw SR_{Red} values and a percentage transformation (with all SR_{Red} expressed as a percentage of the lake's pre-fire SR_{Red} at $\tau = -1$, thus expressing effects as additive changes) to test the robustness of logarithmic transformation. We report the comparison of different transformations in Fig. S4.

Difference-in-Differences regression

Difference-in-Differences (DiD) approach enables causal inference by comparing the relative changes in SR_{Red} of burned and control lakes over time, assuming that the two groups would have followed parallel trends without intervention. Thus, any differential post-fire trends observed between the burned and nearby control lakes can be attributed to the fire event.

We used a dynamic two-way fixed effects (TWFE) regression model that generalizes the canonical DiD model to more than two time periods[59,60]. In the context of wildfire impact on lake color, the dynamic TWFE for a given fire models the reflectance $Y_{i\tau}$ of lake *i* at time lag τ after a fire as:

$$Y_{i\tau} = a_i + \beta_\tau + \delta_\tau D_i + \epsilon_{i\tau} \quad (1)$$

Here, α_i is a lake-level fixed effect that absorbs lake-specific, time-invariant factors, for instance the dependence of reflectance on lake size; β_τ is a temporal fixed effect that absorbs all year-specific factors that are common to all lakes, for instance relating to the summer's weather; D_i is a treatment dummy variable indicating if lake i was disturbed by fire; δ_τ describes the effect of the fire on lake color after τ years and is the main estimand of interest; $\epsilon_{i\tau}$ is an error term.

We estimated the causal effect δ_τ as a function of time, by fitting a TWFE regression model for each fire separately using ordinary least squares (OLS)[61]. We included observations from ten years pre-fire ($\tau = -10$ y) to ten years post-fire ($\tau = 10$ y), excluding the year of the fire ($\tau = 0$ y) to avoid ambiguity in treatment status and observation errors associated with smoke and haze. To ensure identifiability, we constrained the δ_τ for $\tau = 0$ to sum to zero[60]. Thus, the estimated δ_τ is to be interpreted as the effect of the fire on lake color, specifically SR_{Red}, relative to the pre-fire mean. This effect is multiplicative with respect to pre-fire SR_{Red} due to the log transformation. The least-squares fitting also yielded an estimate of the uncertainty of δ_τ in the form of a covariance matrix reflecting the sum-to-zero constraint of the pre-fire effects.

To test the assumption of parallel trends essential to DiD causal identification, we used the estimated pre-fire δ_τ for $\tau < 0$. We expect $\delta_\tau = 0$ for $\tau < 0$ if control and burned lakes followed the same trajectories before the fire. Deviations from this expectation are indicative of violations of the parallel trends assumptions and treatment exogeneity[62]. We quantified the deviations using the standard deviation of pre-fire δ records, a measure of how far the pre-fire δ deviated from zero, and discarded fires with a standard deviation greater than 0.1. Causal identification using TWFE is also challenged by heterogeneous treatment effects and staggered treatments[59,63]. We avoided these challenges by fitting a separate TWFE model to each fire, limiting heterogeneity by restricting to a small region and eliminating multiple treatment events.

To assess whether the fire signal persists beyond a decade, we re-ran the DiD regression on a subset of 22 fires during 2005–2009 with at least 15 years of post-fire Landsat coverage,

extending the window to τ = −5 to +15 y. All pre- and post-DiD quality checks remained the same.

On characterizing the fire impacts, we summarized each fire's post-fire δ_τ trajectory with two scalar metrics: the 90th percentile (δ_{peak}) and the mean (δ_{mean}), which capture the peak and average fire impacts during the ten-year post-fire period, respectively. For a conservative estimate, we used the 90th percentile rather than the maximum to reflect the sustained peak response rather than a single anomalous year. We additionally computed the recovery year of each fire, defined as the first post-fire year at which δ_τ fell within ±10% of the pre-fire SR_{Red} baseline and remained so for the following year. The 95% confidence intervals (CI) of median δ_{peak}, median δ_{mean}, and number of not-recovered fires were computed by bootstrapping over fires while propagating each fire's estimation uncertainty based on its coefficient covariance.

Controls on fire-induced lake color change

We evaluated four fire and physiographic controls, namely burn severity, pre-fire lake color, permafrost probability, and vegetation, on lake color response at the fire level (δ_{peak} and δ_{mean}).

The severity of each fire was characterized by differences in Normalized Burn Ratio (dNBR), a widely used optical index for assessing burn severity[64]. Mean dNBR of each fire was computed using the intersection of fire polygons[49] and the Canada Landsat Burned Severity product[64], an annual burn severity composite with 30 m resolution. Pre-fire baseline lake color was represented by the average SR_{Red} of burned lakes in the summer preceding the fire. In addition, we computed the mean permafrost probability[65] and mean pre-fire leaf area index (LAI) of each fire. Mean LAI in the summer before fire was computed from the BU-LAI dataset[66], a global bi-monthly LAI estimation from 2000 to 2022 with 500 m resolution, and used as a proxy for vegetation cover and fuel availability. Finally, we computed the OLS regression and R^2 coefficient between each pair of control and metric.

To test whether lake size also modulates the fire response, we repeated the DiD analysis separately for small and large burned lakes for each fire. A global area threshold of small and large lakes was computed as the bottom and top tertiles of all burned lakes pooled from all fires, respectively. Then, for each fire, only small or large burned lakes were selected for DiD regression, while the full-set control lakes were included to absorb consistent lake- and time-fixed effects. Differences in δ_{peak} and δ_{mean} between small and large lakes of each fire were then tested with the Wilcoxon signed-rank test.

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Competing Interest

The authors declare no competing interests.

Data and Code Availability

A Code Ocean capsule containing all data and code relevant to this manuscript has been created for peer review.

All data products, including the GEE-generated lake color composites, fire metrics, and the DiD regression outputs, have been uploaded to Zenodo (https://doi.org/10.5281/zenodo.24094491). The data is currently under restricted access and will be made public upon manuscript acceptance. All Landsat products used in our analysis are publicly available on Google Earth Engine. All code developed for this manuscript can be accessed via Github (https://doi.org/10.5281/zenodo.24094910).

Authorship Contribution Statement

Q.C. and S.Z. conceived and designed the study. Q.C. led the research, compiled and processed the datasets, and performed the analyses. S.Z. contributed to data analysis and interpretation of the results and provided funding support. A.B. contributed to the interpretation of the results, supervised the work, and acquired funding. Q.C. wrote the manuscript with input from all authors. All authors reviewed and approved the final manuscript.

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